Transfer functions for carbon sequestration, nitrogen retention and nutrient release capability in forest soils based on soil texture classifications

Callesen, Ingeborg

Publication date:
2003

Document version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Callesen, I. (2003). *Transfer functions for carbon sequestration, nitrogen retention and nutrient release capability in forest soils based on soil texture classifications*. Forest & Landscape, University of Copenhagen.

Skov & Landskab

Danish Centre for
Forest, Landscape
and Planning

KVL DEN KGL. VETERINÆR- OG LANDBOHØJSKOLE

Bülowsvej 17
1870 Frederiksberg C
Telefon 3528 2828
E-mail kvl@kvl.dk

Ingeborg Callesen

Transfer functions for carbon sequestration, nitrogen retention and nutrient release capability in forest soils based on soil texture classification

PhD Thesis

Title (en): *Transfer functions for carbon sequestration, nitrogen retention and nutrient release capability in forest soils based on soil texture classification*

Title (da): *Skovjordes evne til at binde kulstof og kvælstof og til at frigive næringsstoffer i relation til teksturklassifikation*

Supervisors:

Professor, Dr. forest et habil J. Bo Larsen, Institut for Økonomi, Skov og Landskab, Den Kgl. Veterinær- og Landbohøjskole, Frederiksberg.

Afdelingsleder, Ph.D. Karsten Raulund-Rasmussen, Afdeling for Skovøkologi, Forskningscentret for Skov & Landskab, Hørsholm.

Financed by:

Forskningsstyrelsen

Forskningscentret for Skov & Landskab, Hørsholm

Assessment committee:

Professor Gunnar Abrahamsen, Norges Landbrukshøgskole, Ås, Norge

Professor Peter Högberg, Sveriges Lantbruksuniversitet, Umeå, Sverige

Professor Ole K. Borggaard, Den Kgl. Veterinær- og Landbohøjskole, Frederiksberg, Danmark

Defended for the acquisition of the Ph.D. degree in the area forest ecology, on October 23, 2003.

Printed by Samfundslitteratur Grafik, Frederiksberg, Danmark

ISBN: 87-7611-027-3

CONTENTS

Papers ***(available via http://dx.doi.org/ or upon request from ica@skydebanen.net)***

I: **Callesen, I., Raulund-Rasmussen, K., Bilde Jørgensen, B., Johannsen VK, 2006.** Growth of beech, oak, and four conifer species along a soil fertility gradient. Baltic forestry, 12:14-22.

IV: **Callesen, I., Raulund-Rasmussen, K., Westman, CJ and Tau-Strand, L, 2007.** Nitrogen pools and Carbon:Nitrogen ratios in well-drained Nordic forest soils related to climate and soil texture. Boreal Env. Res. 12:681-692. pdf

VI: **Callesen, I., K. Raulund-Rasmussen, 2004.** Base cation, aluminum and phosphorus release potential in Danish forest soils. J. Plant Nutr. Soil Sci. 167:169-176.

doi: 10.1002/jpln.200321202

III: **Callesen, I., Liski, J., Raulund-Rasmussen, K., Alriksson, A., Olsson, M.T., Tau-Strand, L., Vesterdal, L., Westman, C.J. 2003.** Soil carbon stores in Nordic upland forest soils - relationships with climate and site variables. Global Change Biology 9: 358-370.

doi:10.1046/j.1365-2486.2003.00587.x

II: **Vejre, H., I. Callesen, L. Vesterdal, and K. Raulund-Rasmussen, 2003.** Carbon and Nitrogen in Danish forest soils - contents and distribution determined by soil order. Soil Science Society of America Journal. 67: 335-343.

V: **Callesen, I., K. Raulund-Rasmussen, P. Gundersen og H. Stryhn, 1999.** Nitrate concentrations in soil solution below Danish forests. Forest Ecology and Management 114:71-82.

doi:10.1016/S0378-1127(98)00382-X

1. DANSK RESUME

Samfundet efterspørger goder fra skovene, og de efterspurgte goder ændrer sig i takt med samfundsudviklingen. For øjeblikket er miljøgoder som kulstofbinding, rent grundvand og skovjordens evne til at frigive næringsstoffer på langt sigt i fokus. Klimaændringer og menneskeskabt luftforurening med fx svovl, kvælstof og ozon påvirker skovenes vækstvilkår, men også processer i jordbunden. Der er ikke enighed om, hvorvidt luftforureningen er skadelig for vækst og sundhed på kort og langt sigt, hvorimod det er alment accepteret at kvælstoftilførslen er medvirkende årsag til at skovenes vækst har været stigende. Ligeledes hersker der usikkerhed om, hvordan et varmere klima og ændrede nedbørsmønstre vil påvirke produktion og nedbrydning af organisk stof i skovøkosystemet, og dermed de kulstofpuljer som er resultatet af processerne. Udfordringen består i at opnå de efterspurgte miljøgoder og afbøde evt. negative konsekvenser af de ændrede vækstbetingelser.

Aktuelle kulstofpuljer i jordbunden, evnen til at binde nyt kulstof, til at være vækstmedium for træer, og til at modstå virkninger af forsurende luftforurening knytter sig til jordbundens egenskaber. Tekstur benyttes generelt i bonitering af jord, fordi vand og næringsstofforsyning, samt buffer- og filteregenskaber afhænger af fx indholdet af ler, silt og sand. Underjordens egenskaber er vigtige, fordi træerne henter næringsstoffer fra dybere lag, som tilføres jordoverfladen med nåle- og løvfald.

I afhandlingen beskrives, hvordan underjordens tekstur kan bruges som indikator for jordbundsudvikling og stofomsætning i skovjorde.

Skovjorde inddelt i klasser for i) grovsandede jorde, ii) finsandede og/eller lerholdige jorde og iii) lerede jorde blev benyttet i en karakteristik af i) kulstof og kvælstofpuljer i skovjorde, ii) nitratudvaskning fra skovjorde og iii) skovjordes evne til at frigive næringsstoffer og neutralisere syre. Undersøgelserne bygger på datasamlinger af skovjorde, som er karakteriseret ved fysiske og kemiske analyser, samt egne indsamlinger og analyser. Almindeligt anvendte træarters vækst i relation til klima, samt fysiske og kemiske jordbundsegenskaber blev undersøgt i et forsøg med træarter plantet på tidligere dyrkede jorde.

De anvendte teksturklasser viste sig at kunne karakterisere mange af de nævnte miljøgoder. Kvælstofpuljer, kvælstoftilgængelighed og nitratudvaskning blev kvantificeret i transfer funktioner baseret på klassifikationen. Grovsandede jorde bandt større kulstofpuljer end lerede jorde, mens det omvendte gjaldt kvælstofpuljer. Omsætning af organisk stof og kvælstoftilgængelighed, vist som nettonitrifikation og lave kulstof:kvælstof forhold, var størst i lerede jorde, der også udvaskede mere nitrat end grovsandede jorde. Evnen til at frigive næringsstoffer på langt sigt var meget

lav i grovsandede jorde, lidt større i finsandede og/eller lerholdige jorde, og størst i lerede jorde, især hvis disse var kalkholdige. Træproduktion, især hvad angår arterne eg og bøg, øgedes med jordens næringsstofstatus, der kunne karakteriseres ved lerindhold og pH i underjorden. Lerindhold og pH i underjorden foreslås som indikatorer for jordens næringsstofstatus. Disse parametre adskiller samtidig jorde med stor bufferevne mod forsuring fra jorde med lav bufferevne. Det betyder, at lerede jorde er langt mere robuste overfor forsuring end grovsandede jorde.

Som en substitut for ændret klima blev relationen mellem klima og skovjordes kulstof- og kvælstofpuljer undersøgt ved hjælp af de samme teksturklasser langs en klimagradient fra tempereret til boreal skov. Undersøgelsen viste, at kulstof og kvælstofpuljer voksede med årsmiddeltemperatur og årsnedbør. Det blev fortolket som en effekt af større produktion af biomasse, men også som en følge af ufuldstændig nedbrydning af organisk stof på næringsfattige jorde. Analyser af effekten af ændret klima på kulstofpuljer i jorden bør derfor inddrage både vækst og nedbrydnings-processer, og skelne mellem jorde med forskellig næringsstofstatus.

Det konkluderes at underjordens tekstur, inddelt i tre klasser, er anvendelig i en kvantitativ beskrivelse af skovjordes kulstof- og kvælstofpuljer, nitrattilgængelighed og langsigtede evne til næringsstof-frigivelse. Under danske forhold er teksturklassifikationen sammenfaldende med mineralogiske forskelle, idet næringsholdige, reaktive mineraler er næsten fraværende i grovsandede jorde. Jordens egenskaber skal tages i betragtning, når konsekvensvurderinger af luftforurening og klimaændringer på kulstofbinding, nitratudvaskning, og langsigtet næringsstofforsyning foretages. Underjordens tekstur og pH er centrale parametre. De opstillede transferfunktioner viser, at underjordens tekstur og pH udgør en generel karakteristik af skovjordes kvalitet med hensyn til de undersøgte miljøgoder.

.

2. ABSTRACT

Quantification of environmental benefits related to the state and function of forest soils are lacking. Quantitative soil data from Danish and Nordic soil surveys were used to establish empirical relationships between environmental functions and soil properties using soil texture classification as a transfer function. Investigated states and functions were tree growth, accumulation of carbon and nitrogen in forest floors and mineral soil, nitrogen mineralisation and net nitrification, nitrate leaching, and release of phosphorus and base cations by acid hydrolysis. A classification based on subsoil texture into fine, medium, and coarse textured soils separated soils in respect of nutrient status, carbon and nitrogen storage, nitrate availability, and capability for nutrient release by weathering. The volume growth of beech and oak was correlated with availability of soil nutrients. Texture class was seen as a driving variable for pedological development of soils, illustrated by texture-class-related differences in short-term and long-term release of aluminium and base cations in repeated dilute nitric acid extracts. The proportion of base cations to base cations + aluminium was termed based index. The base index of long-term release indicated that coarse textured soils had a more acid mineralogy than medium and fine textured soils. In a proposed classification of soil nutrient regimes, the long-term base index was used to distinguish podsolised soils, i.e. soils with accumulation of reactive Al-oxides, from not podsolised soils. Subsoil pH was less than 5 in podsolised soils and 5-7 in not podsolised soils. Subsoil pH was therefore suggested as an indicator of soil nutrient regime.

The texture classification was used in a climosequence study of carbon and nitrogen storage in forest soils ranging from dry cold boreal forest to humid cool temperate forest. Carbon and nitrogen pools in forest floors and in mineral soil increased with mean annual temperature and mean annual precipitation. Soil texture classes were differently related to carbon and nitrogen storage. High carbon pools were observed in B horizons of podsolised soils in nutrient poor coarse and medium textured soils in the cool humid climate that characterises Denmark. Organic horizons accounted for high carbon pools in nutrient poor soils as compared to low carbon pools in nutrient rich soils. Carbon:Nitrogen ratios were distinguished by texture class and genetic soil horizons. Low carbon:nitrogen ratios indicated a higher degree of decomposition in fine textured soils. Coarse textured soils had the highest carbon:nitrogen ratios.

Changes in soil organic matter storage or nitrogen retention in response to a changing climate and atmospheric nitrogen deposition depend on both biomass production and mineralisation of organic matter. Here, analyses of accumulated carbon and nitrogen pools in soils indicated that these processes

behave differently according to the inherent soil nutrient status that may be characterised by soil texture class and subsoil pH. These parameters are therefore suggested as indicators of forest soil qualities like growth, nitrogen storage, transformation and retention, and long-term nutrient release.

3. PREFACE

During the years 1999-2003 I was a Ph.D. student at The Danish Forest and Landscape Research Institute, Hørsholm and The Royal Veterinary and Agricultural University, Frederiksberg, Copenhagen. My office was located at The Danish Forest and Landscape Research Institute, Department of Forest Ecology.

Supervisors were Dr. forest et habil J. Bo Larsen, Professor in silviculture at The Royal Veterinary and Agricultural University, and Ph.D. Karsten Raulund-Rasmussen, Head of Department, The Danish Forest and Landscape Research Institute, Department of Forest Ecology.

The thesis is based on six original papers. Three are published, and three are in review. Co-author statements are printed in Annex II. Published papers are referred to by author and year. Papers in review are referred to by roman numerals. Tables and figures referred in italic may be found in the original papers:

I. Callesen, I., K. Raulund-Rasmussen, B. Bruno Bilde Jørgensen, and V. Kvist-Johannsen. Compared growth of two broadleaved and four conifer species along a gradient in soil nutrient availability. Submitted.

II. Vejre, H., I. Callesen, L. Vesterdal, and K. Raulund-Rasmussen (2003). Carbon and nitrogen in Danish forest soils – contents and distribution determined by soil order. Soil Science Society of America J. 67: 335-343.

III. Callesen, I., J. Liski, K. Raulund-Rasmussen, M.T. Olsson, L. Tau-Strand, L. Vesterdal, and C.J. Westman (2003). Soil carbon stores in Nordic well-drained forest soils – relationships with climate and texture class. Global change biology 9(3): 358-370.

IV. Callesen, I., K. Raulund-Rasmussen, C.J. Westman, L.Tau-Strand, M.T. Olsson. Nitrogen pools and Carbon:Nitrogen ratios in Nordic well-drained forest soils. Submitted.

V. Callesen, I., K. Raulund-Rasmussen, P. Gundersen, and H. Stryhn (1999). Nitrate concentrations in soil solutions below Danish forests. Forest Ecology and Management 114: 71-82.

VI. Callesen, I. and K. Raulund-Rasmussen. Nutrient release capability in Danish forest soils by repeated dilute nitric acid extraction. Submitted.

4. INTRODUCTION

4.1 Background and objectives

Environmental services like carbon sequestration, maintenance of ground water quality and long-term soil fertility are linked to the cycling of carbon, nitrogen, nutrients and water in forest ecosystems. Climate change, carbondioxide fertilisation, nitrogen enrichment, ozone pollution, and soil acidification may influence ecosystem processes like forest growth or soil respiration in either positive or negative direction depending on the time perspective and site properties (Schwalm & Ek, 2001; Jarvis & Linder, 2000; Schulze, 1989; Brodin & Kuylenstierna, 1992; Nellemann & Goul Thomsen, 2001). Precise forecasting of the effects of changing growth conditions on ecosystem processes is presently impossible, but the study of ecosystem function across current environmental gradients may reveal the course of change. Forest soils are central to the environmental services from forestry that is currently requested.

Forest soils in the broadest sense may be defined as soils that developed under forest cover, and, in a more narrow sense, as soils that are presently influenced by forest cover (Fisher & Binkley, 2000). The first definition would encompass most soils in Denmark, and the second currently about 11.3 % of the land area (Anon. 2002a).

Properties and processes operating at different time scale influence the current status and function of soils. An operational definition of forest soils may take into account that soils are mostly in transition due to changes in land use and climate during the Holocene. Soils have been rejuvenated during this period by processes and impacts such as solifluction, wind erosion, ecosystem succession, land use changes, wild fires, and management.

Forest soils develop organic layers also termed forest floors from annual litter inputs. The litter layer may be absent for some period of the growing season due to rapid mineralisation. Nutrients are taken up in deep soil layers and transferred to the forest floor with litter, a mechanism termed base pumping. This characteristic pattern of nutrient cycling constitutes the definition of a forest soil irrespective of previous land use.

Forest crop rotations are long compared to agricultural crops, and forest soils are therefore characterised by infrequent soil disturbance. These may typically be by the event of wind throw or soil preparation at stand replacement, and by minimal use of lime, fertilisers and pesticides. The uppermost soil horizons in humid areas are acid because of natural acidifying processes in industrialised areas intensified by elevated sulphur and nitrogen deposition. Forest soils are defined here as the soil compartment in a forest ecosystem irrespective of age, because future development will be governed by the characteristic forest nutrient cycling. Some soil properties change rapidly after afforestation of agricultural soils, and others are persistent. As an example, decreased concentrations of calcium, magnesium and potassium, termed base cations, and pH in top soil can be documented only three to four decades after afforestation (Andersen *et al.*, 2002), whereas phosphorus application may be traced for centuries (Arrhenius, 1934).

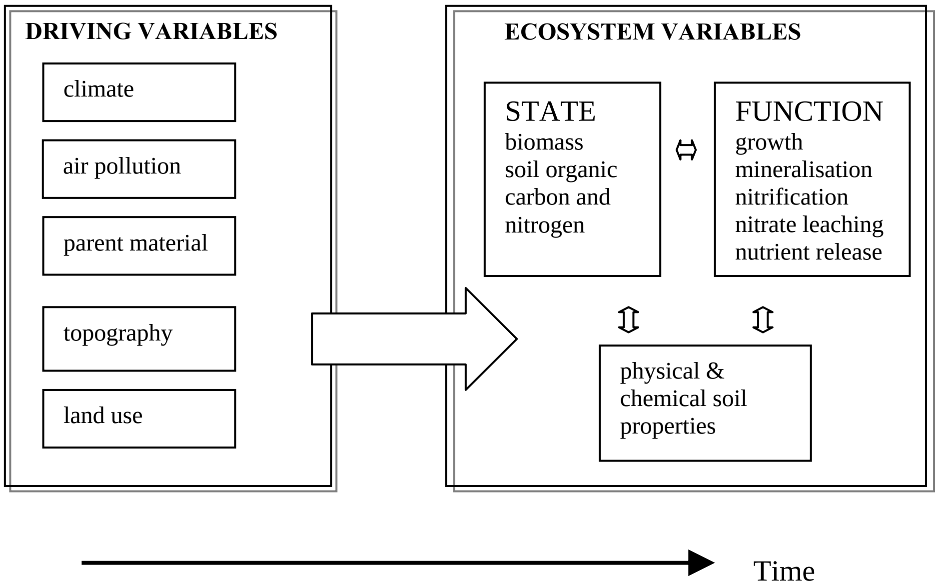


Figure 1. *Independent driving variables and examples of ecosystem state factors. Ecosystem properties are influenced by driving variables, state factors and time (modified from Fisher & Binkley, 2000).*

Jenny (1980) introduces state factors as qualitative determinants of ecosystem properties, and suggests that quantitative interpretations may be possible. Biomass accumulation, e.g. carbon and nitrogen pools in soils and chemical soil properties are functions of climate, organisms, topography, parent material, time and random error including all other possible influences. Fisher and Binkley (2000) put up a different concept that distinguishes abiotic and anthropogenic driving variables from ecosystem variables. Driving variables are such as climate, air pollution, parent material topography, and land use. Ecosystem state and function emerge from the driving variables and interact with physical and chemical soil properties over time (Figure 1).

Updated information about the status of carbon pools, nitrogen retention and nutrient status of forest soils is scarce. Forest production is assessed in field inventories of stand height and basal area. Soil science has a tradition of morphological description of soils by their visual appearance: organisation in horizontal layers, texture, colour, structure and porosity, and a physical and chemical characterisation of these so-called genetic horizons (Buol *et al.*, 1997). The question remains, as suggested by Jenny (1980):

Can soil morphology be quantitatively linked with environmental benefits such as carbon storage, nitrogen retention and long-term soil fertility?

Soil texture is one aspect of soil morphology. It is well established that the fertility in young unweathered soil is linked to texture, seen as more favourable conditions in loamy compared to sandy soils, in respect of tree growth (Carmean, 1975; Hägglund & Lundmark, 1977), mineralisation of nitrogen (Reich *et al.*, 1997), and nutrient release by weathering (van der Salm, 1999). Carbon pools are observed to increase with clay contents (Oades, 1988; Grigal & Ohmann, 1992; Homann *et al.*, 1995; Jobbágy & Jackson, 2000). Being linked to a range of different functions, soil texture may be termed a general indicator for forest soil quality (Seybold *et al.*, 1998).

Climate is a driving variable that influences ecosystem processes like growth and mineralisation. Globally, soil carbon pools increase with decreasing temperatures and increasing precipitation (Post *et al.*, 1982; Jobbágy & Jackson, 2000), but regional patterns may be different.

Here, it is tested whether soil texture either as a class variable or a continuous variable can distinguish state and function in forest soils. The following state factors are considered: forest productivity, storage of soil organic carbon and soil organic nitrogen. The studied functions are: net nitrification and nitrate leaching, and nutrient release capability. Some of the links outlined in Figure 1 will be evaluated by quantitative analyses. It will be investigated whether the influence of soil texture and climate can be demonstrated in lithosequences, i.e. different parent materials, and climosequences of gradients in temperature and precipitation.

Based on texture analyses of genetic soil horizons in 50-100 cm depth, soil profiles are divided into coarse, medium and fine textured soils (Table 1). The idea is to distinguish soils with different functioning in terms of e.g. growth and mineralisation (Figure 1). Fine textured soils have more than 10% clay, which is thought give adequate nutrient supply by weathering (Table 1). Medium textured soils have 5 to 10% clay *or* a content of fine silt *or* more than 50% coarse silt + fine sand. Coarse textured soils have more than 95% coarse sand, and may impose nutrient constraints to soil functions, which may also be the case in medium textured soils.

Table 1. *Definition of texture class. Weighted average of 50-100 cm (weight % clay, silt, or fine sand multiplied with layer thickness / 50 cm), less than 2 mm fraction.*

Texture classes	
Fine:	>10% clay[1]
Medium:	<5% clay and (>5% fine silt or >50% coarse silt + fine sand) or 5-10% clay
Coarse:	others

[1]Clay <0.002 mm; fine silt 0.002-0.02 mm; coarse silt 0.02 – 0.063 mm; fine sand 0.063-0.2 mm.

The definition of texture classes is motivated by the fact that subsoil properties, as suggested by Bornebusch (1933), are important to soil nutrient status due to base pumping in forest ecosystems. The classes may also reflect geomorphology, and separate mixed glacial tills (fine and medium textured soils) from sorted glaciofluvial deposits (coarse textured soils), and sandy aeolian deposits (medium and coarse textured soils).

Holdridge (1947) defined world life zones and associated vegetation based on mean annual temperature and mean annual precipitation. The same parameters are used here as climate proxies in climosequence analysis.

The thesis is based on investigations of soils that are part of forest ecosystems in Denmark, Finland, Norway, and Sweden. First, the texture classification is applied on a population of Danish forest soils to check how forest soils are separated by the classification (Section 5). Production as related to a gradient in soil fertility is treated in Section 6. Next, climate and texture class and the relationship with carbon and nitrogen storage in forest soils is investigated (Section 7), to be followed by analysis of nitrogen availability and nitrate leaching as related to soil texture class and landscape features in Section 8. Nutrient release capability of mineral soil as related to soil texture class is treated in Section 9. Based on these investigations, transfer functions and indicators of forest soil quality are discussed in Section 10.

Each of these ecosystem states and functions are subject to experimental research and debated by separate scientific communities. Their discussion cannot be treated in depth; the aim here is to investigate the idea of using soil texture and climate in state factor analysis, as suggested by Jenny (1980) and Fisher & Binkley (2000), to link these agendas.

4.2 Study objects and investigations

The study objects were forest soil profiles in northern nemoral and in boreal forests. The focus was on Danish forest soils also including soils in western Denmark that have been influenced by arctic climate in the Pleistocene (Hansen, 1965).

Studies of soil morphology and tree growth (paper I and VI) were conducted in two long-term experiments established by the Danish Forest and Landscape Research Institute in 1964-65 (Holmsgaard & Bang, 1977) and in 1973-74 (Danish Forest and Landscape Research Institute, unpub.). Soil profiles from a field experiment comprising 10 coniferous species, beech and oak planted in 13 blocks across Denmark, and 5 sites in a field experiment of 8 broadleaved species, Grand fir and Norway spruce, and one site in a demonstration forest planted by the private co-operation Silkeborg Plantningsforening were included in a study of nutrient release capability (paper VI). Study I is a growth-soil-site study that uses growth and soil profile data from 8 sites in the 1964-65 experiment that were situated on former agricultural land. The study sites are indicated on the map in Figure 2 and described in appendix I.

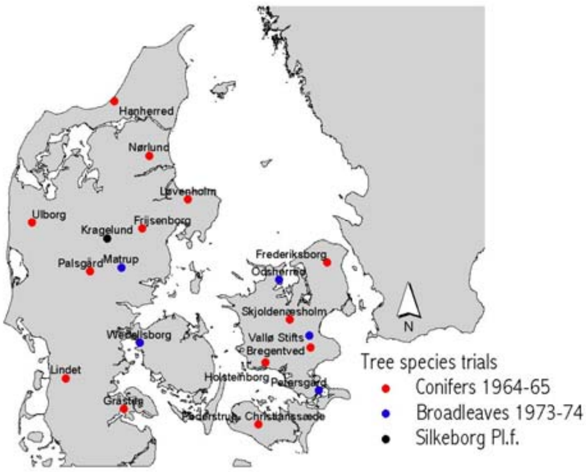


Figure 2. *Investigated soil profiles in tree species trials in Denmark (paper I and VI). Profile descriptions and site data are found in Appendix I.*

A forest soil database of soil profiles described and analysed during the 70s, 80s and 90s (Raulund-Rasmussen & Callesen, 1999) was compiled for the study of soil organic carbon and nitrogen pools in the Nordic countries (Vejre *et al.*, 2003 and paper IV). Soil profile descriptions according to both international standards (e.g. FAO, 1990) and national field keys from Finland, Sweden, Norway and Denmark had been used. Protocols established prior to database compilation were used to secure that only soil data analysed by comparable chemical methods were included in the analyses.

The soil profiles are mapped in Figure 3, and vegetation zone limits between nemoral, boreo-nemoral and boreal forest according to Påhlsson *et al.*, (1984) are indicated. Soil profiles are located from latitude 55 °N to 70 °N and longitude 5 °E to 27 °E and constitutes a climosequence from cool and humid to cold and dry including sites in nemoral, boreo-nemoral, southern and northern boreal forest. A North-South gradient in mean annual temperature (-2 °C to 8.5 °C), and nitrogen deposition (~1 to more than 40 kg N ha^{-1} y^{-1}), and a gradient from East to West in mean annual precipitation (282 to 2270 mm y^{-1}) characterise the area (Callesen *et al.*, 2003 and paper IV).

The studied soil profiles, in total 234, were developed on aeolian, fluvial, and glaciofluvial parent materials and on glacial till in forest stands dominated by Norway spruce (66 %), pine, *Pinus sylvestris* L. (20%), oak (2%) and beech (10%), or other species such as birch and exotic conifers (2%).

A Danish monitoring programme of soil water nitrogen supplied data on nitrate and ammonium. Composite samples collected 2 to 6 times in 25 cm soil depth intervals to 100 cm soil depth during winter months from 1986 to 1993 were extracted in 1 M KCl (Østergaard & Mamsen, 1990). Descriptions of soil morphology and chemical properties of one soil profile per site were available from a national soil survey. In the survey, soil texture, calcium carbonate and humus content were analysed in all soil profiles in samples originating from genetic horizons. 29 profiles were analysed for total nitrogen, exchangeable cations, and pH (Breuning Madsen *et al.* 1992).

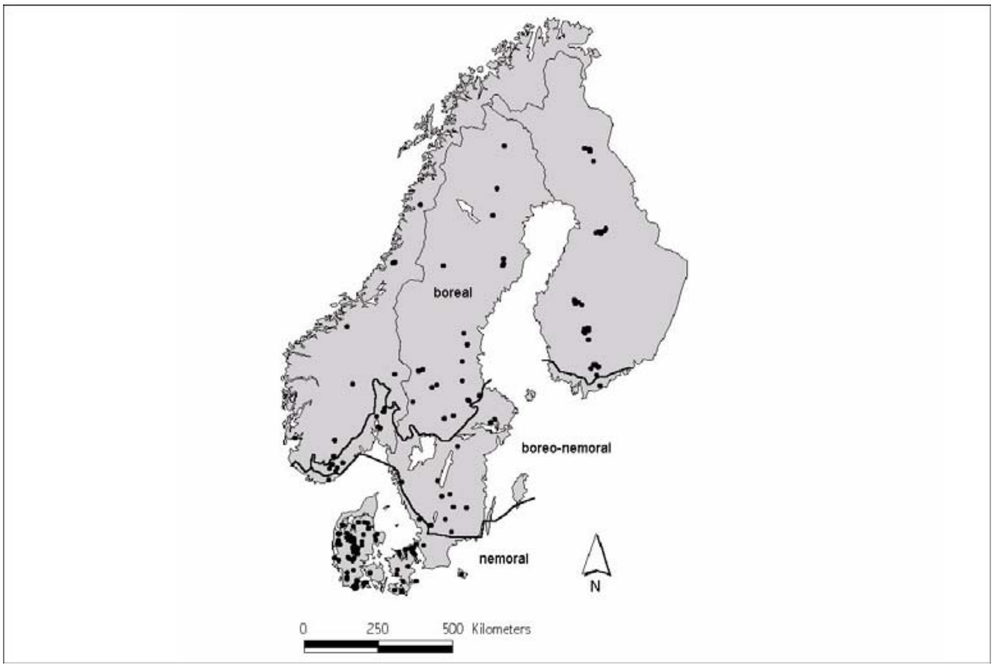


Figure 3. *Investigated forest soil profiles in the Nordic countries (Vejre et al., 2003 and paper III + IV)*

5. SOIL TEXTURE CLASSIFICATION

Subsoil texture class can be assessed at the site level in field surveys. Site is defined as a land unit of similar growth conditions (Barnes *et al.*, 1998). How does the texture classification suggested in Table 1 characterise Danish forest soils?

A population of Danish forest soils is illustrated in Figure 4. Clay and silt were 86% correlated in the data, and thus summed on the z-axis. The position of a profile in the diagram revealed sorting of the parent materials by e.g. wind or water. Profiles that are located close to an axis are probably developed in sorted deposits, whereas profiles developed in unsorted materials, characteristic for glacial tills (Hansen, 1965), are located in the centre of the diagram.

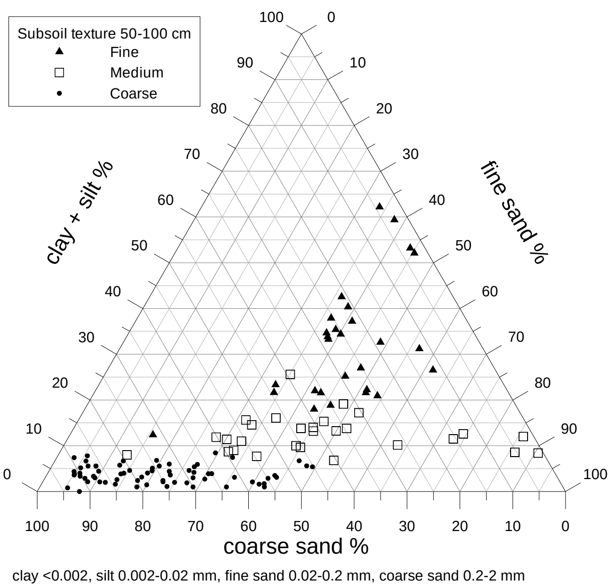


Figure 4. *Soil profiles distributed to texture class (profiles used in Vejre et al., 2003). Subsoil fine silt is 86 % correlated to clay. Weighted (by thickness of horizon) average percentage of clay + silt, fine sand and coarse sand in depth 50-100 cm. Data from Raulund-Rasmussen and Callesen (1999).*

In general, unsorted soils were medium and fine textured, whereas those that contained less than 5 % coarse sand are likely to be sorted by wind (90% fine sand) or by sedimentation in slowly moving water (>50% clay and silt).

In coarse textured soils, the proportion of coarse sand ranged from 50 to nearly 100 %, and the clay + silt content was less than 5%.

Texture classification in The Danish Soil Classification is based on distribution of clay, silt, fine sand and coarse sand. Less than 5% clay delimit sandy soils, 5% to 15% clay are clayey sand or sandy clay, and >15% clay are clay soils (Madsen & Platou, 1983). In the classification presented here, all coarse textured soils and about one fifth of medium textured soils would be classified as sandy soils. The remaining medium textured soils and one third of fine textured soils would be clayey sand or sandy clay, and remaining fine textured soils would be clay soils. The present classification, dividing at 10% clay rather than 15% clay, appears to reflect natural divides in particle size distributions in a population of 140 Danish forest soils. Limits set at 8% clay + silt and 18% clay + silt would roughly replace the classification rules set up in Table 1, since soils with less than 8% clay + silt also had high coarse sand contents. In the field, clay content can be assessed within a "window" of about 3 percent points (Soil Survey Division Staff, 1993). Separation of the three texture classes in the field should be quite possible. It is concluded that the texture classification represents natural divides in the population of Danish forest soils. These divides are likely to reflect geomorphology.

6. TREE GROWTH AS RELATED TO GROWTH ENVIRONMENT

Tree growth has been reported to exceed empirical yield tables in Europe over the last 50 years. Meanwhile, the vitality and stability of forests have been questioned due to increasing levels of air pollution, events of extreme climatic stress, coinciding with observations of forest die-back (Pretzsch, 1999).

Improved silviculture, tree breeding, the fertiliser effect of nitrogen deposition, increased atmospheric carbondioxide concentrations and a changing climate have been suggested as explanations for increasing growth. The general trends of increasing growth (Spiecker, 1999) and scattered reports of decreasing growth and declining vitality in response to air pollution and acidification (e.g. Schulze, 1989; Nellemann & Goul Thomsen, 2001) indicate that observational growth-soil-site studies will need continuous updates. Still, yield tables may be inadequate in predicting growth, since they are retrospective. In a changing growth environment, predictions of growth should rest on models based on growth processes as determined by growth factors such as climate, water, and nutrient availability (Schwalm & Ek, 2001). Soil and climate as described in site classification could thereby separate sites that are likely to experience climatic stress or nutrient stress from more robust sites.

6.1 Soil nutrient regime and soil moisture regime

Water and nutrient supply is a quality of the soil (Seybold *et al.*, 1998). Site classification is a tool used by forest managers in characterisation of the growth environment. Part of a site classification is the assessment of forest soil quality including the rating of soil nutrient regime. The amounts of nutrients and their availability through cycling are inferred from physical and chemical properties of the forest floor, top mineral soil, or subsoil. Also adverse chemical properties such as strong acidity or lack of oxygen are considered in evaluation of nutrient supply. Some soil properties can be roughly estimated in field surveys, aided by regional soil information systems and pedotransfer functions. Examples are the significance of soil texture and humus content to water holding capacity (Breuning Madsen & Platou, 1983), cation exchange capacity (Krogh *et al.*, 2000), and bulk density (Tamminen & Starr, 1994). Forest soil fertility investigations are often restricted to the uppermost soil layers, since root turnover and nutrient uptake is concentrated in the organic layer and upper mineral soil horizons. Chemical characteristics of soil nutrient regime are exchangeable cations, exchangeable acidity, and pH. Humus form and vertical distribution of organic matter, C:N ratio, and nitrogen mineralisation characteristics (gross, net or potential nitrogen mineralisation), and extractable phosphorus are commonly used indicators of forest soil fertility, whereas soil texture is a common physical indicator (Rehfuess, 1999; Schoenholtz *et al.*, 2000). Ground vegetation and humus form are used as field indicators of soil fertility (Kabzems & Klinka, 1987b; Wilson *et al.*, 2001).

Soil moisture regimes are described by precipitation deficit in the growing season (if any), root exploitable soil volume, skeletal content, available water capacity, soil texture, soil structure, soil density, and influence of ground water or lateral water, e.g. (Carmean & Li, 1998; Hägglund & Lundmark, 1977; Tamminen, 1993).

The question remains if soil nutrient regime and soil moisture regime are linked with tree growth, forest vitality and stability in a way that allows use of soil based indicators of site quality for e.g. growth. Relationships with forest vitality and stability are not treated here.

6.2 Site quality – relative productivity of six tree species

A direct way of assessing site quality for a particular tree species is by using height development as a bioindicator. The growth of different tree species may respond differently to strong frosts, wind, salt deposition, and soil physical and chemical parameters. Growth-site-soil relationships are specific to tree species, or groups of species with similar ecology within regions (Carmean, 1975). Selection of variables for characterisation of soil properties in the long term and growth environment should not include parameters that are influenced by the interaction between tree species and soil properties such as properties of the forest floor (see Binkley & Giardina, 1998). Therefore, properties of the subsoil or the entire soil volume exploited by roots are better suited in growth-site-soil evaluations than e.g. ground flora and topsoil properties, which may be changed by land-use in the short term.

Choice of tree species at reforestation of existing forests or afforestation of agricultural land influence future environmental benefits such as e.g. carbon sequestration in biomass and soils, nutrient cycling, and hydrology, since tree species interact with growth environment (Binkley & Giardina, 1998; Augusto *et al.*, 2002). Different tree species planted in even-aged adjacent stands are suitable for investigation of the interaction of tree species with site. Regional growth-soil-site studies, i.e. empirical relationships between tree height at index age and physiography are numerous, as shown in the review of economically important North American species by Carmean (1975).

However, height at index age may be an inappropriate biotic indicator of site quality, especially when comparing different tree species, because it is not indicative for the shape of the growth curve. Biotic indicators, also including dynamic indicators of site quality and their relationship with availability of nutrients in soils was studied in a Danish tree species trial. The stands were planted in 1964-5 in 8 blocks on formerly cultivated soils showing a strong gradient in soil fertility from nutrient poor, acid sandy soils to fertile calcareous loamy tills. Growth of Sitka spruce, Douglas fir, Norway spruce, larch, beech and oak in relation to the chemical properties of one representative soil profile at each site was analysed by use of a site quality parameter for height and volume growth estimated in difference equations (paper I).

(1) Height growth $\Delta H / \Delta t = a\hat{H}^{b} e^{-c\hat{H}}$

(2) Volume growth $\Delta V / \Delta t = a\hat{V}^{b} e^{-c\hat{V}}$

These equations were used to calculate annual increment in stand height and volume. They describe a growth curve where growth accelerates, reaches a maximum rate, and then declines (Leary *et al.*, *in rev.*). Parameters for the equations were fitted from records of stand height and volume recorded three to four times during stand development. Parameter "b" controlled the acceleration of the curve, and "c" the rate decline. These were common to each species, whereas "a", the maximum growth rate, was estimated for each tree species at each site, and thus characteristic for the response of the species to the site.

The selection of soil and site variables was inspired by the literature on forest site classification, ecological land classification, and forest soil fertility, e.g. (Carmean, 1975; Kabzems & Klinka, 1987a; Wilson *et al.*, 2001; Köhler, 1984) aiming at quantitative description of nutrient and water availability. Soil and site variables used were soil texture, i.e. average clay, silt and fine sand per cent (w/w %) in 50-100 cm soil depth weighted by horizon thickness, element pools in the top 100 cm mineral soil (kg ha^{-1}) of phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg), the maximum pH in subsoil (B or C horizon), C:N ratio of the top mineral soil (0-15 cm depth), drainage class, annual mean temperature, and precipitation surplus (mm) in the growing season (paper I).

Pools of extractable phosphorus and exchangeable potassium in soil depth 0 to 100 cm, and maximum subsoil pH at the 8 sites are illustrated in Figure 5. Phosphorus and potassium pools, and subsoil pH (*paper I, Table I*) were ranked along the x-axis and compared with cumulative frequency distributions of nutrient pools and pH that were calculated from forest soil data in Danish soil surveys e.g. Breuning Madsen & Jensen, (1985), Breuning Madsen & Olsson (1995), and Raulund-Rasmussen & Callesen (1999). Data from 167 soil profiles had adequate data for extractable phosphorus, and 222 profiles had data for exchangeable potassium. It is concluded that investigated soils in the tree species trials were representative of the range of nutrient regimes in Danish forest soils. The eight study sites represent low as well as high pools of phosphorus and potassium, and subsoil pH in the range from acid to near neutral (Figure 5).

Soil and climate variables were strongly interrelated. Temperature, clay and silt were positively correlated with pH and nutrient pools (up to r~0.95). The gradient in soil variables was much stronger than the climate gradient (*paper I, Table II*), and the first principal component (PC1) in a principal components analysis (PCA) accounted for 64% of the variation. It was interpreted as a soil nutrient availability gradient. The most fertile soils (CHR, SKJ and FRE) had 13 to 23% clay in 50-100 cm soil depth and a subsoil pH that ranged from 5.5 to 7.7. The poorest soils had less than 5% clay and silt and a subsoil pH around 4.

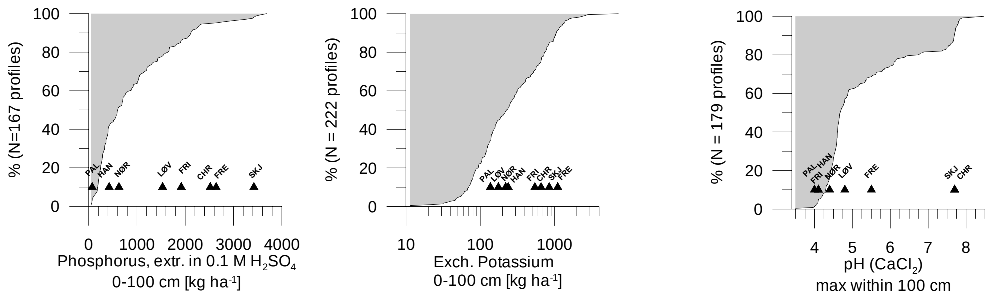


Figure 5. *Extractable phosphorus, exchangeable potassium, and subsoil pH at 8 investigated sites in the 1964-65 tree species trial as compared to cumulative frequency distributions of phosphorus, potassium and subsoil pH in Danish forest soils based on data from Danish forest soil databases. Site name acronyms: PAL - Palsgård, HAN - Hanherred, NØR - Nørlund, LØV - Løvenholm, FRI - Frijsenborg, SKJ - Skjoldenæsholm, CHR - Christianssæde, FRE - Frederiksborg.*

There was a positive relationship between growth and soil fertility synthesised in PC1 (Figure 6; *paper I, Table VI*). However, the six investigated tree species did not respond consistently to water and nutrient availability. The volume growth of beech and oak was best described by the gradient in soil nutrient availability, whereas the volume growth of Sitka spruce, Norway spruce, Douglas fir and larch was unrelated to PC1 (*paper I, Table VII*). A larger data set might result in soil-site relationships that show statistical inference in line with other published studies for e.g. Norway spruce (Köhler, 1984; Hägglund & Lundmark, 1977).

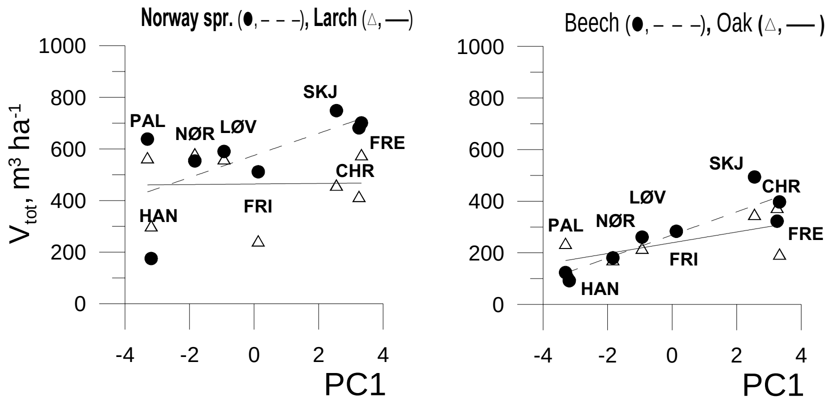


Figure 6. *Total production of Norway spruce, larch (m^3 ha^{-1} stemwood), beech and oak (m^3 ha^{-1} stemwood and branches) 1964 - 1998. PC1 is an index for increasing soil fertility, based on PCA analysis including subsoil texture, nutrient pools, pH, C:N ratio, temperature and precipitation surplus. Soil fertility increases along PC1 (paper I). Site name acronyms: PAL - Palsgård, HAN - Hanherred, NØR - Nørlund, LØV - Løvenholm, FRI - Frijsenborg, SKJ - Skjoldenæsholm, CHR - Christianssæde, FRE - Frederiksborg.*

Standardised site quality parameters for volume growth rate of beech, oak, larch and Norway spruce compared in Figure 7 demonstrated no clear relationship with nutrient availability for Norway spruce and Larch. Site quality expressed as volume growth rate showed little variation on sites with high nutrient pools and a high pH (sites SKJ, FRE and CHR in Figure 5), in contrast to nutrient poor sites, where lack of water, nutrients, salt spray and strong wind may have reduced growth. This observation supports the feasibility of a regional Norway spruce yield table for nutrient rich loamy soils in Eastern Denmark (Magnussen, 1983) represented here by the site Christianssæde (CHR) (Figure 7).

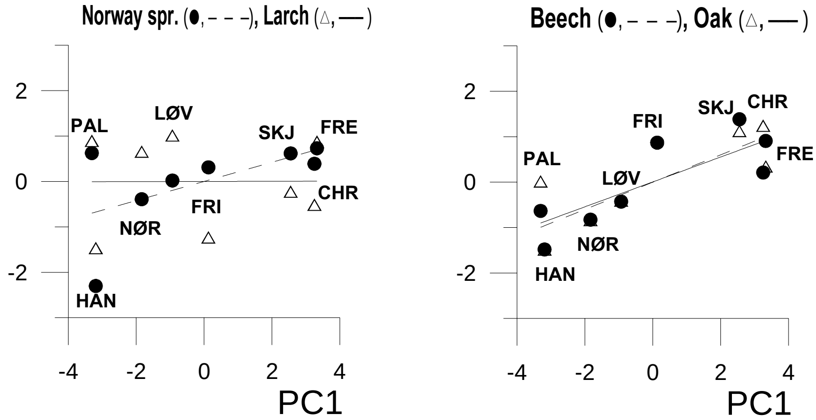


Figure 7. *Growth rate for total production of Norway spruce, larch, beech and oak estimated in difference equations*:

$\Delta V / \Delta t = a\hat{V}^{b} e^{-c\hat{V}}$

Y-axis: standardised volume growth rates (a). "a" is an indicator of site quality. X-axis: Index for soil fertility based on subsoil texture, nutrient pools, pH, C:N ratio, temperature and precipitation. Soil fertility increases along PC1. Site name acronyms: PAL - Palsgård, HAN - Hanherred, NØR - Nørlund, LØV - Løvenholm, FRI - Frijsenborg, SKJ - Skjoldenæsholm, CHR - Christianssæde, FRE - Frederiksborg.

In addition to the observational studies (paper I), the response to increased nutrient availability can be examined in fertiliser experiments. There are no general signs of foliar nutrient deficiency in Danish spruce stands apart from nitrogen deficiency, but positive growth effects of fertilisation with phosphorus and potassium alone are reported. At some sites, nitrogen may not be the primary growth limiting nutrient, a trend that is enhanced by the last five decades of elevated nitrogen deposition (Vejre *et al.*, 2001). Also oak and beech are likely to respond to fertilisation, as indicated by the strong response to soil fertility (Figure 7). The analysis of volume growth data in the tree species trial confirmed the hypothesis that productivity of forest trees is linked to soil fertility, and that subsoil texture is linked to fertility indicators like nutrient pools, pH and C:N ratios.

7. CARBON AND NITROGEN POOLS IN FOREST SOILS

Carbon sequestration and nitrogen retention are desired qualities of forest soils that need quantification. Soils accumulate organic carbon and nitrogen through the action of soil organisms and vegetation. The carbon and nitrogen cycles are linked in photosynthesis, and carbon and nitrogen thus accumulate in live and dead biomass.

Organic carbon is fixed as carbondioxide from the atmosphere through photosynthesis and returned by tree respiration, or by decomposer activity in the soil. Environmental controls on production and decomposition of organic matter include factors like temperature, humidity, availability of nutrients, time, and events like forest fire (Oades, 1988). The carbon retention time in live biomass and soil organic carbon can range from hours up to hundreds of years (Oades, 1988). Net primary production increases with increasing temperature in Europe (Scarascia-Mugnozza *et al.*, 2000). The same relationship does not apply to carbon mineralisation that, apart from temperature, may depend on e.g. nitrogen availability expressed as C:N ratios (Persson *et al.*, 2000), or availability of other nutrients or water.

Human activity has changed the nitrogen cycle in forests in industrialised and densely populated countries after the Second World War by increasing nitrogen emission and thus atmospheric nitrogen deposition (Vitousek *et al.*, 1997). Soil pools of organic carbon and nitrogen change in consequence of fluxes that are generated by e.g. growth, decomposition, mineralisation, nitrification, leaching and denitrification. Pools are not indicative for fluxes of carbon and N. Large carbon and nitrogen pools may emerge from low production, and extremely slow decomposition. High production and incomplete decomposition that leads to formation of recalcitrant humus with long residence time in soils may also result in large soil pools of carbon and N. The pools reflect the outcome of these processes.

7.1 Soil organic carbon, nitrogen pools and C:N ratios in a climosequence

It is held that soil carbon pools decrease with increasing temperature for any level of precipitation at global scale (Post *et al.* 1982). This trend was not confirmed by a regional investigation of Nordic well-drained forest soils. The relationship was tested with multiple regression based on a data set of 85 coarse and 92 medium textured soils. The analysis showed that soil organic carbon (C) increased with increasing temperature and precipitation from about 4 kg C m^{-2} to 14 kg C m^{-2} at an increase in mean annual temperature (MAT) from 0 °C to 8 °C and an increase in mean annual precipitation (MAP) from 500 to 1000 mm. The lines in Figure 8 indicate, for soil texture class coarse and medium, the temperature and precipitation that yield the same amount of soil carbon based on parameters in the regression. In a cold climate, medium textured soils had higher carbon pools than coarse textured soils, and opposite in the cool humid climate (Figure 8). Carbon in coarse textured soils responded more to increases in precipitation than medium textured soils. Large pools in the cool humid climate could be attributed to humus rich spodic horizons and to litter accumulation in organic layers (Vejre *et al.*, 2003).

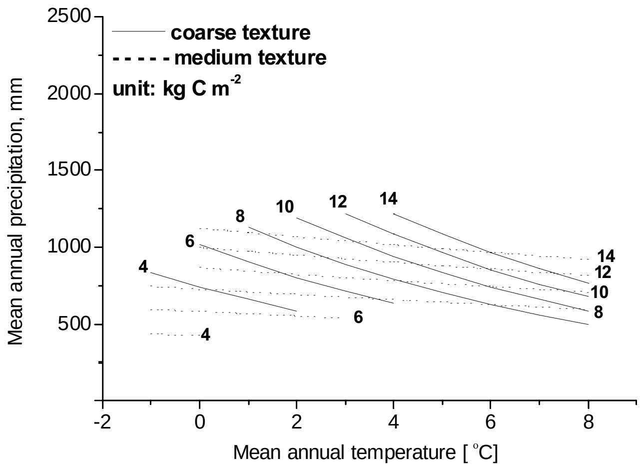


Figure 8. *Soil carbon in relation to mean annual temperature and mean annual precipitation. Calculated Carbon pools in 0-100 cm mineral soil + forest floor, based on parameters in Callesen et al., 2003, Table 3. Example: Medium soils, 4 kg C m*$^{-2}$*: log (Carbon, kg m*$^{-2}$*)= - 2.79 + 0.014 MAT, °C +1.29 logMAP, mm. Rearranges to MAP =* $10^{(\log 4 + 2.79 - 0.014\ MAT)/1.29}$.

The increase in carbon pools with increasing temperature and precipitation could be attributed to storage in organic layers as well as mineral soil horizons. In coniferous stands, organic layer carbon increased with temperature and precipitation from about 1 kg C m^{-2} in a boreal climate to 4 kg C m^{-2} in a nemoral climate (Figure 9). Accumulation of O horizons at a rate of 0.03 kg C m^{-2} y^{-1} in spruce stands on nutrient rich soils is reported 29 years after afforestation of agricultural land in Denmark (Vesterdal *et al.*, 2002). Carbon pools in organic layers in coniferous forest soils were about 3.9 kg C m^{-2} (*Vejre et al., 2003, Table 2*). The number of years required to reach this carbon pool at the rates presented by Vesterdal (op. cit.) would be more than 100 years. However, accumulation depends on litter production and mineralisation that may be rapid on the fertile agricultural soils that are now afforested. The estimate of 3.9 kg C m^{-2} reflects forest management, species composition, age structure and soil types in the analysed data set and may not be a representative estimate of Danish forest floors. A stratified sampling design in respect of soil texture class, age and species composition of Danish forests would provide a more central estimate of the true accumulation of forest floor carbon at present.

The focus on well-drained soils reversed the trend of increasing carbon pools with decreasing temperature stipulated by Post *et al.* (1982), and this surprising result was attributed to the focus on well-drained soils. These examples stress the need for stratified sampling designs in carbon accounting.

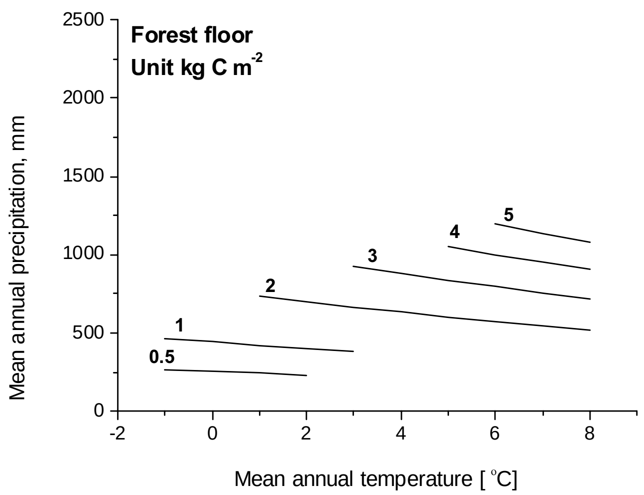


Figure 9. *Carbon pools in forest floor of coniferous stands in relation to mean annual temperature and mean annual precipitation based on parameters in Callesen et al., 2003, Table 3. Example: 2 kg carbon m^{-2}: log Carbon, kg m^{-2} = - 3.31 + 0.027 MAT, ℃ +1.25 logMAP, mm.*
Rearranges to: MAP = $10^{(\log 2 + 3.31 - 0.027 MAT)/1.25}$.

The nitrogen cycle is different from the carbon cycle by the fact that microorganisms in soils are responsible for nitrogen fixation, apart from a minor contribution of oxidised nitrogen brought about by lightning. Nitrogen is relocated in living biomass by transfer from old to new tissue, and is lost from ecosystems by denitrification or leaching of nitrate.

Soil pools of organic nitrogen increased similar to carbon pools with increasing temperature and precipitation. On average, the range was estimated to 0.1 kg N m^{-2} to 0.7 kg N m^{-2} from cold dry to cool humid climate (Figure 10). The range in soil nitrogen pools was 0.05 to 1.65 kg N m^{-2} (paper IV). Relationships of nitrogen pools with climate depended on texture class. Fine textured soils lacked representation across the study area and interpretation of any correlation with climate would be inappropriate. Medium textured soils had higher soil nitrogen pools than coarse textured soils in a cold and dry climate, while nitrogen pools in texture classes coarse and medium were similar in a cool humid climate. In Denmark, the soil texture classification was also reflected by the morphogenetic soil classification. The soil profiles had been classified according to the 5th Edition of Soil Taxonomy (Soil Survey Staff, 1992). A stratification by soil order showed that base-rich Alfisols, of which 89% were developed on fine textured soils and calcareous fine textured soils (Table 2), had nitrogen pools of 0.75 kg N m^{-2} and a total C:N ratio of 12 in contrast to nitrogen pools of 0.50 kg N m^{-2} in base-poor Spodosols with C:N ratio 28 that were to 77% developed on coarse textured parent material (*Vejre et al., 2003, Table 3*). Total C:N ratio in a soil profile seems to be indicative for the size of the nitrogen pool and the degree of decomposition.

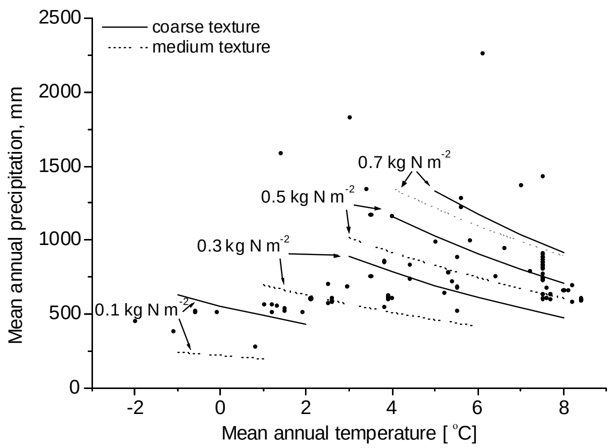


Figure 10. *Nitrogen pools in Nordic forest soils. Lines indicate temperature and precipitation combinations of similar accumulation in kg N m^{-2}. The dataset used in regression are shown as dots. Parameters in the regression may be found in paper IV, Table 2.*

Decomposition and mineralisation of root and foliage litter by soil organisms gradually lead to formation of organic matter with a higher nitrogen concentration relative to carbon concentrations, and thus decreasing C:N ratios in decomposing organic matter. C:N ratios were calculated and analysed in genetic horizons and sections of 10 cm soil depth (paper IV). Characterisation of C:N ratios by soil depth and genetic horizon indicated differences in age of organic matter and possibly influence of nitrogen deposition that covaried with temperature (paper IV). C:N ratios increased in the order fine, medium and coarse in 0-10 and 20-30 cm depth and in the organic layer. In sections from 40 to 60 cm, C:N ratios in boreal soils were lower than in nemoral soils for the same texture class (Figure 11), indicating a higher degree of decomposition in deep layers, but a low degree of decomposition or a low litter quality in the upper layers. Analysed by genetic horizons, both carbon and nitrogen concentrations and the C:N ratio decreased with increasing soil depth in the Danish data. In A and B horizons, C:N ratios were generally low in Alfisols and high in Spodosols (*Vejre et al., 2003, Figure 2*). Analysed by soil order, there was a trend of decreasing C:N ratios with soil depth (*Vejre et al., 2003, Figure 2*), while the decrease in C:N ratios in A, E, B and C horizons was not seen when the stratification by soil order was omitted (*Vejre et al., 2003, Table 4*). In nemoral soils, C:N ratios were about 20 - 30 in coarse and medium textured soils in all 10-cm sections, and less than 20 in fine textured and calcareous fine textured soils, whereas a stronger contrast was seen in boreal soils, ranging from 40 in upper layers to 10 in lower layers (Figure 11).

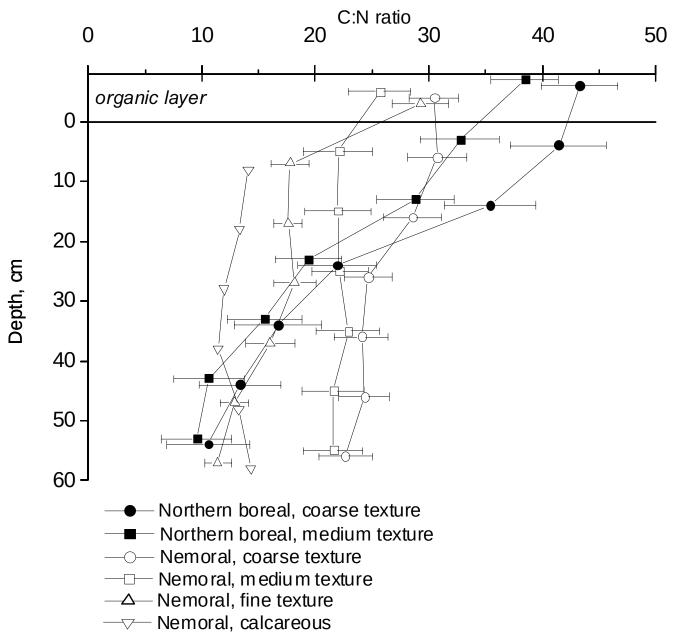


Figure 11. *C:N ratios in 10 cm sections calculated for two selected combinations of temperature and precipitation. Northern boreal: 2 °C and 500 mm y^{-1}. Nemoral: 7.5 °C and 800 mm y^{-1}.*

Table 2. *Cross tabulation of taxonomy (Soil Survey Staff, 1992) and soil texture class as defined in Table 1.*

Soil order	Spodosol	Alfisol	Inceptisol	Entisol
Number of profiles	34	18	23	31
Texture class		Per cent		
Coarse	77	0	39	82
Medium	23	11	39	9
Fine	0	67	17	9
Calcareous[1]	0	22	4	0
Total	100	100	100	100

[1]Calcareous: Fine textured soils that have more than 1% $CaCO_3$ within 100 cm soil depth.

Both carbon and nitrogen pools increased with temperature and precipitation, but soil age, forest fire frequency and fire intensity, vegetation, land use history, and the current nitrogen deposition gradient may also explain observed differences.

The positive relationships with climate are specific to the region characterised by its Holocene climate- and vegetation history, and cannot be extrapolated to other regions or beyond the investigated precipitation or temperature levels. Soils in a cold climate with high precipitation are likely to be hydromorphic or organic, judged by the carbon and nitrogen pool estimates given by Post *et al.* (1985) for e.g. boreal rain forest of 32.2 kg C m^{-3} and 1.5 kg N m^{-3}. Organic soils dominate large areas in the boreal zone (Soil Survey Staff, 1998) and may explain the global trend of increasing carbon and nitrogen accumulation with decreasing temperature (Post *et al.*, 1982; Post *et al.*, 1985). The focus on well-drained soils (Vejre *et al.*, 2003, Callesen *et al.*,2003 and paper IV) allowed the study of production and decomposition as influenced by a lithosequence described by texture class and a climosequence described by mean annual temperature and mean annual precipitation. The analyses document how much carbon and nitrogen is stored in forest soils and where it is located, and allows the hypothesis that carbon in well-drained soils will not be mineralised in response to increased temperature. Nutrient poor soils seem to hold recalcitrant carbon pools. Thereby, northern well-drained forest soils may have an unrealised potential for carbon accumulation at a temperature increase. In areas with elevated nitrogen deposition that stimulates growth (Nadelhoffer *et al.*, 1999) forest soils are capable of increasing the current carbon and nitrogen stores, provided that mineralisation of carbon and nitrogen is not stimulated by chronic nitrogen deposition. The increasing trend for carbon storage in organic layers (Figure 9) and upper mineral soil layers along the climate gradient (*Callesen et al., 2003, Figure 3*) support the hypothesis that carbon pools may be increasing in response to a longer growing season.

In the boreal zone, forest fires reduce carbon and nitrogen pools in the forest floor as demonstrated by a study of fire frequency on Islands (Wardle *et al.*, 1997). Small islands with low fire frequency accumulate thicker organic layers than larger islands that experience natural fires more frequently. Forest fires may stimulate growth and thus litter production on nutrient rich sites when nutrients tied up in organic layers are mineralised by fire, but also impoverish ecosystems at dry and nutrient poor sites (Tamm, 1950). Within the last century, it is likely that control of forest fires has lead to humus build up and thus increasing carbon and nitrogen pools in organic layers.

Increasing temperatures has been hypothesised to reduce carbon pools as an effect of increased soil respiration. Carbon and nitrogen accumulation in forest floors along the gradients in temperature and precipitation (Figure 9 and *paper IV Figure 3*) does not indicate that temperature controls the carbon or nitrogen accumulation, i.e. that higher temperature (and humidity) accelerate decomposition of organic matter relative to production of litter. However, the role of decomposition relative to litter production cannot be separated with the present data. This is a weakness of studying soil carbon and nitrogen pools rather than respiration or mineralisation fluxes in relation to growth environment. The carbon and nitrogen characteristics of organic matter in the investigated soils indicate that litter quality and decomposition stage vary, depending on soil texture class, soil depth and climate.

The upper 50cm of the mineral soil appear to be the major zone of carbon storage (*Callesen et al., 2003, Figure 3*), and also of carbon mineralisation activity. In a laboratory incubation experiment, carbon mineralisation in depth 30-50 cm was less than 5 % of the total mineralisation rates in two nutrient rich and one nutrient poor soil profile in Denmark. Carbon mineralisation rates in the organic layer accounted for 80 % of the activity and 0-10 cm soil depth for 5 to 10% (Persson *et al.*, 2000). This indicates that carbon stored in deep soil layers is not subject to intense decomposer activity and may be recalcitrant. Yet, soil layers deeper than 50cm represent significant carbon pools that should be included in carbon accounting.

The study of soil profiles compiled in databases may imply a bias. The soil profile data were collected over a 20-year period. During that time nitrogen deposition has been increasing (e.g. Vitousek et al., 1997), accumulating in forests at a rate of 5 to 20 kg N ha^{-1} y^{-1}. Locally, accumulation rates may have been higher. In consequence, a difference over 15 years of perhaps 75 to 300 kg N ha^{-1} would arise. If one third of this amount has accumulated in soils, the difference between a profile sampled in 1975 or in 1995 would be 25 to 100 kg N ha^{-1} or 0.025 to 0.1 kg N m^{-2}. The population mean of 0.6 kg N m^{-2} implies that up to 17% (*Vejre et al., 2003,*

Table 2) could be ascribed to temporal sampling bias if all soils were sampled in the 1970s. Compared to a typical error of 30% on soil carbon pool estimates (de Wit & Kvindesland, 1999) the temporal bias would be less than sampling error and hard to detect. Bulk density sampling error and stone content assessment are major sources of error in soil element pool calculations. It also suggests that changes in soil carbon storage at time periods of decades may be hard to verify by traditional sampling of soil profiles. There is a need for development of new methods. Chronosequences as used by Vesterdal et al. (2002) is a good option to follow time trends as a substitute for the lack of time series of carbon storage.

7.2 C pool estimation: Texture class or morphogenetic classification?

C pool estimates by texture class (Callesen *et al.*, 2003) or by morphogenetic classification (Vejre *et al.*, 2003) are based on the same dataset. In Callesen *et al.* (2003), the Danish data were extended with data from Sweden, Norway and Finland. Carbon pool estimates for Denmark and a climate typical for western Denmark with annual mean temperature of 7.5 °C and 800 mm y^{-1} are compared in Table 3.

Estimates by soil order are more precise than those obtained by texture class. The 95% confidence limit (based on standard errors of the mean) for coarse soils was [10.9 - 17.5 kg C m^{-2}] and that for Entisols [10.5 - 13.4 kg C m^{-2}]. This is a consequence of using texture, and not the degree of soil development expressed as humus accumulation in O and B horizons. Depending on e.g. age of the profile, micro topography and vegetation history, the B horizon of a coarse textured soil could be poor or rich in illuvial carbon as a result of podsolisation. Spodosols have to meet criteria for carbon content of at least 0.6% carbon and a thickness of no less than 2.5 cm (Soil Survey Staff, 1992). As a consequence, the Spodosol estimate of 14.6 kg C m^{-2} exceeds the estimate of the less podsolised Entisols (11.9 kg C m^{-2}).

Table 3. *Estimates of soil carbon in O horizon + 0 - 100 cm soil depth at a temperature of 7.5 °C and a precipitation of 800 mm y^{-1} (Callesen et al., 2003) and by soil order (Vejre et al., 2003, Table 4).*

Texture class	Estimate, 95% CL kg carbon m^{-2}	Soil order	Estimate, 95% CL kg carbon m^{-2}
Coarse	13.8 (10.9 - 17.5)	Spodosols	14.6 (13.1 - 16.4)
		Entisols	11.9 (10.5 - 13.4)
Medium	10.9 (9.1 - 13.0)	Inceptisols	10.8 (9.4 - 12.4)
Fine	10.2 (8.3 - 12.5)	Alfisols	8.8 (7.6 - 10.3)

7.3 Conclusions and perspectives for carbon and nitrogen accounting

In conclusion, soil organic carbon and nitrogen increase along gradients in climate from boreal to nemoral climate, and for both carbon and nitrogen the increase is stronger in coarse textured soils. This indicates an unrealised potential for further carbon storage in soils, aided by increased nitrogen availability from deposition. Low nitrogen pools and high C:N ratios in boreal forest soils indicate that nitrogen limitation prevails. Soil texture classes are confounded with morphogenetic soil classification in Denmark, which may explain the successful use of texture class along with climate in predicting carbon pools in the Nordic data set. An investigation of carbon pools in nutrient rich soils along a climate gradient would give interesting information about carbon accumulation in the case of high nutrient availability.

Using driving variables of soil development in analysis of carbon and nitrogen storage, namely climate and soil texture class, according to the model outlined in Figure 1, proved to be a meaningful concept. It emphasises that observed regional and global trends of carbon storage with climate may very well be opposite if other factors like drainage, land use and disturbance history, and air pollution level are not *ceteris paribus*. Influencing factors like land use history and air pollution could not be investigated with the present data. For this purpose, designs where these factors are fully crossed would be useful, however hard to establish.

Development of methods to follow trends in soil carbon storage are needed, and results presented here stress that sampling designs should be stratified by driving variables like climate, parent material and nitrogen deposition regime.

8. NITROGEN AVAILABILITY AND NITRATE LEACHING

It has been put forward that increased fluxes and pools of nitrogen in terrestrial ecosystems will cause nitrogen saturation that can be monitored as nitrate leaching (Aber *et al.*, 1989; Nihlgård, 1985; Gundersen *et al.*, 2003). Nitrate contamination of drinking water is a threat to ground water resources. The standard for quality of water intended for human consumption is set at 50 mg nitrate dm^{-3} or 11.3 mg NO_3^--N dm^{-3} (Council directive 98/83/EEC). Time series of soil water chemistry recorded at forest monitoring sites show temporal increases in nitrate concentrations in soil water when nitrogen cycling is decoupled. Disturbances that detach the timing of nitrification and plant uptake such as strong thinning operations, clear-cutting, or defoliation caused by drought, salt deposition or insect infestation have promoted nitrate leaching (Gundersen *et al.*, 2003). Nitrification is a precondition for leaching of the mobile nitrate anion. However, nitrate may be immobilised by rhizosphere heterotrophs or root uptake, and nitrification activity monitored as nitrate in soil solution will not be detected in such cases.

Large soil nitrogen pools and low C:N ratios were found in fine-textured soils, and nitrogen contents and C:N ratios decreased with soil depth (paper IV). The same factors that are related to soil nitrogen pools, may also explain nitrogen mineralisation and nitrification. A study of soil nitrogen turnover in beech and Norway spruce stands in an European transect from latitude 41° to 64° N shows a positive, but weak correlation between net nitrogen mineralisation in the range 0 – 0.02 kg N m^{-2} y^{-1} and soil nitrogen pools in the range 0.1 - 0.9 kg N m^{-2} (Persson *et al.*, 2000). The question arises as to what extent nitrate and ammonia concentrations in soil water reflect nitrogen pools and C:N ratios in Denmark, and further if nitrifying soils can be characterised by texture class.

Systematic information on nitrate concentrations in soil leachate from forests has not been available until a national monitoring campaign was initiated in 1986 (Østergaard & Mamsen, 1990). These monitoring data were used to evaluate the degree of nitrogen saturation monitored as nitrate leaching in Danish forests, and the influence of soil type, forest management type and forest size on nitrate leaching (Callesen *et al*., 1999).

Nitrate concentrations in the Danish survey of 111 forest plots were monitored during the years 1986 to 1993 by sampling at 2 to 6 occasions during wintertime from October to April. In total about 25 samplings per site were performed during the 7-year period. Nitrate in soil depth 0 - 25 cm was seen as indicative for nitrification activity, whereas nitrate in soil depth 75 - 100 cm was interpreted as leached nitrate. 93% of the sites had median concentrations that were within the drinking water standards (Callesen *et al*., 1999). 30% of the sites had median concentrations above 2 mg NO_3^--N dm^{-3} indicating loss of nitrogen from the forest ecosystems.

Stratification by soil texture class explained variation in nitrate concentrations in soil depth 75-100 cm. Humus soils (6.0 mg NO_3^--N dm^{-3}), fine textured soils (1.9 mg NO_3^--N dm^{-3}) and medium soils (1.7 mg NO_3^--N dm^{-3}) had higher concentrations than coarse textured soils (0.8 mg NO_3^--N dm^{-3}). Tree species and soil types were confounded. Broadleaves were mainly situated on fine textured soils and conifers on coarse and medium textured soils (Table 4). However, nitrate leaching was not distinguished by tree species when a classification into broadleaf and conifer sites replaced soil texture class in the analysis. If an interaction between soil type and tree species exists, it cannot be tested in the present data set (Callesen *et al*., 1999).

The analysis was elaborated by including soil chemical data to test links between soil nutrient availability and net nitrogen mineralisation. Soil profiles at 29 out of 111 forested sites had been sampled and analysed for pH, exchangeable base cations, total C, and N; and soil texture (Breuning Madsen *et al.*, 1992). Mineral soil pools of base cations, subsoil pH and texture class were calculated in parallel to the growth-soil-site study (paper I). These soil chemical parameters were examined in relation to net nitrogen mineralisation during winter months. To characterise soil nitrogen transformation, the maximum and median concentrations of ammonia and nitrate recorded in the 7-year monitoring period in soil depth 0 - 25 cm were analysed in principal component analysis (PCA). Along with the nitrogen variables potassium (range 1 to 145 g m^{-2}), calcium (range 9 to 2970 g m^{-2}), magnesium (range 0.7 to 244 g m^{-2}), maximum subsoil pH (range 3.9 to 7.8) entered the PCA. Median nitrate concentrations were in the range 0.4 to 15.3 mg NO_3^--N dm^{-3}, maximum concentrations in the range 1.2 to 64.8 mg NO_3^--N dm^{-3} soil solution. Median NH_4^+-N were in the range 0.5 to 4.5 mg NH_4^+-N kg^{-1} soil and maximum NH_4^+-N in the range 1.3 to 54.6 mg NH_4^+-N kg^{-1} soil. The first axis in PCA was a gradient in nitrate (+) and mineral soil pools of potassium, calcium and magnesium (+), pH (+), and C:N (-), explaining 41% of total variation (Figure 12). Plus and minus signifies the sign of the loading, i.e. the direction of the correlation. The second axis (PC2) was characterised by high median and maximum ammonia concentrations explaining 20% of total variation in the data.

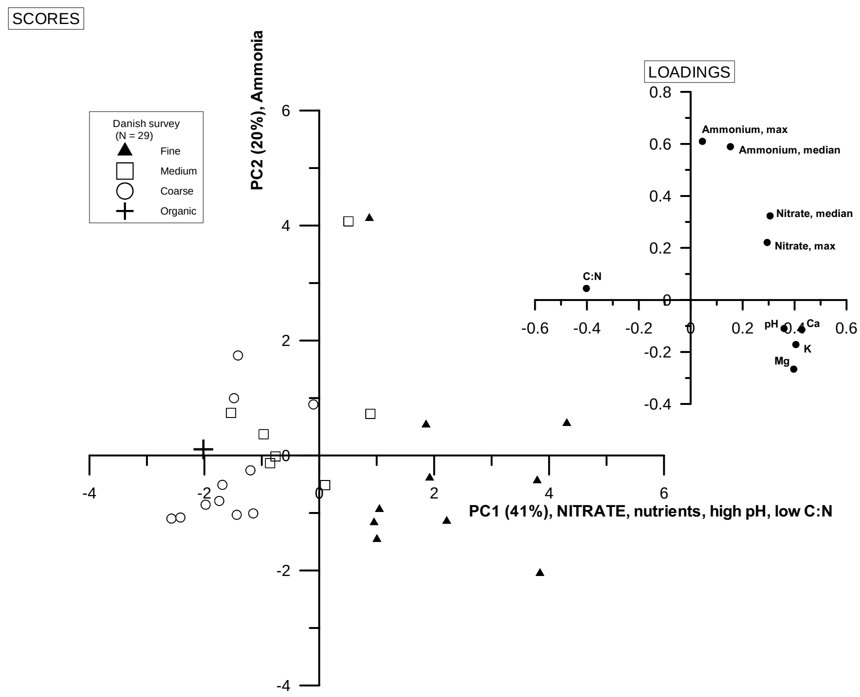


Figure 12. *Score plot and loadings (principal components analysis) of soil nutrient pools, pH, nitrogen mineralisation and nitrification in the top 25 cm soil in 29 soil profiles sampled 1986 – 1993. Median and maximum ammonia and nitrate concentrations.*

Along PC1 sites appeared in the order coarse, medium, and fine (Figure 12). Nutrient rich soils were characterised by the occurrence of nitrate in soil depth 0-25 cm during winter and intermediate concentrations of ammonia (Figure 12). The low level of ammonia and higher level of nitrate concentrations in these soils indicated that nitrification took place. Deposited ammonia may even be nitrified and immobilised during wintertime. This may explain the absence of high ammonia concentrations in fine textured soils.

In comparison to fine textured soils, coarse textured and medium textured soils had no, or very low concentrations of nitrate, and variable ammonia concentrations indicating that net nitrification was not taking place to the same extent as in fine textured soils. Ammonia deposition may govern the level of ammonia concentrations. Two sites had a high PC2 score; both were mature spruce stands closely situated to a westerly forest edge in areas with intense animal husbandry. Emitted ammonia is deposited within short distance from the source in comparison to nitrous oxides (Skeffington & Wilson, 1988). High ammonia loads may explain the soil ammonia concentrations, since forest edge deposition of ammonia is much higher than what is found in more protected stands (Beier & Gundersen, 1989). In the data set of 111 sites, sampling points in forests smaller than 10 ha had higher concentrations than forests larger than 50 ha. This observation was interpreted as an effect of forest edges receiving high nitrogen loads as dry deposition.

The analysis of the smaller data set of 29 sites supported the idea that soil texture class separated forest soils with net nitrification from soils where net nitrification was not observed (Figure 12). Texture class separated soils of different nutrient status, pH and C:N ratios represented by PC1. The assumption that nitrate is leached from 75 - 100 cm soil depth in nutrient rich B horizons may lack empirical support. B horizons were deeper in Alfisols in comparison with Spodosols and Entisols. This implies that the 75-100 cm samples in the national survey may be B horizon material, whereas the same depth interval in sandy soils is C horizon (*Vejre et al., 2003, Figure 2*). The average total nitrogen concentration in C horizons was 0.08 mg g^{-1} against 0.30 mg g^{-1} in Bt horizons (*Vejre et al., 2003, Table 4)*. Nitrate concentrations in this depth may thus be a result of in situ biological activity rather than nitrate in percolating soil water. Internal drainage in loamy soils is often hampered by low hydraulic conductivity as compared to coarse textured soils. Therefore, anoxic conditions in loamy soils may lead to denitrification. Investigations of nitrous gas exchange in forest soils would reveal the extent of denitrification taking place in soils with poor internal drainage.

Apart from soil texture, effects of forest management, former land use and forest size explained variation in nitrate concentrations. In the Danish survey (Callesen *et al*., 1999.), newly afforested sites had higher nitrate concentrations than other woodland types. Agricultural soils had high nitrate concentrations after afforestation, especially when weed control reduced nitrogen uptake to the low capacity of newly planted tree seedlings. However, the net nitrification was transitory (Gundersen *et al.* 2003; Callesen *et al*., op. cit.). Most likely, the ability to nitrify in afforested agricultural soils is maintained for a long time. The difference in nitrate concentrations between soil texture classes coarse and fine may reflect different land use. Coarse textured soils may have been marginal for a longer time, and may have a history of *Calluna vulgaris* heathland, whereas fine textured soils may have carried a silvi-pastoral landscape, since beech has dominated forests in eastern Denmark for 2000 years (Bradshaw & Holmqvist, 2000).

Table 4. *National survey of nitrogen mineralisation in forest soils. Cross tabulation of tree species and soil texture class (number of sites~111).*

Texture class	Broadleaves	Conifers
Fine	29	5
Medium	8	32
Coarse	7	26
Humus	1	4

In summary, the quality of soil leachate was within drinking water standards for nitrate at 93% of the sites in the Danish survey during the years 1986-1993. Nitrogen saturation does not seem to be widespread. Soil texture class described variation in nitrate concentrations, whereas tree species did not. The highest winter nitrate concentrations in the upper mineral soil (0-25 cm soil depth) as well as in the potential leaching zone (75 -100 cm soil depth) were found in fine textured soils with low C:N ratios and high nitrogen and nutrient pools. The current analysis of a strong soil fertility gradient and a limited climate gradient show that stratification by soil type gives essential information on nitrogen fluxes that are also reflected by the degree of decomposition expressed as C:N ratio in at 0-15 cm mineral soil depth.

High nitrogen storage and occurrence of net nitrification rests on inherited soil properties reflecting soil nutrient availability in fine textured soils. Soil texture class and subsoil pH are simple parameters that are related to soil nutrient availability (Vejre et al. 2003; Callesen et al. 1999).

9. NUTRIENT RELEASE CAPABILITY

Weathering of minerals supplies forest ecosystems with macro nutrients (P, K, Ca, Mg), micro nutrients (Fe, Mn, Cu, Zn, Mo, B) and beneficial elements (Na, Si, Co, Ni, Se, Al) (Marschner, 1986). Protons are consumed in the weathering process thereby neutralising acidity produced in the ecosystem. Anions like bicarbonate, nitrate and sulphate that are leached with base cations generate acidity. Base saturation of the soil exchange complex will gradually decline if base cations are not replenished by weathering or deposition at the rate by which they are exported or leached.

Soil acidification is a natural process in humid climates, but anthropogenic sources of acidity may generate more acidity. Observations of ongoing acidification have been reported; pH in topsoil has declined in Europe over the last 30–40 years, e.g. in southern Sweden (Falkengren-Grerup *et al.*, 1987, Jönsson *et al.* 2003), Denmark (Pedersen & Bille-Hansen, 1995), and Finland (Westman & Jauhiainen, 1998). This decline is generally explained by acidifying deposition, or increased forest growth, transferring base cations from soil to biomass in excess of weathering inputs (Sverdrup *et al.*, 1992). Accumulation of litter in the organic layer ties up base cations and decreases base cation pools in the mineral soil if the litter is not mineralised.

The assessment of annual weathering inputs is controversial, and no standard method has been established. Along with particle size distribution, mineralogical composition of the parent material determines the kind and amount of elements that are released in the weathering process. Soil moisture, soil temperature, organic ligands, acid and base properties in soil solution and at soil surfaces, and redox potential influence the weathering process (van Breemen *et al.*, 1983).

The parent material in the glaciated region, comprising most of the Nordic countries, contain small amounts of reactive, i.e. weatherable minerals; although the dominant bedrock is acid gneiss and granite, and dominant minerals are quartz and feldspars. Van Breemen *et al.* (1983) defined ecosystem acidification as the ultimate loss of acid neutralising capacity (ANC) by dissolution of primary minerals, and export of released base cations. Due to dissolution kinetics controlled by the environment, the ANC may require infinite time scales to be realised. The mineral assembly determines how the solid phase, the exchange complex, and the soil solution responds to proton loads generated by current deposition pressures and harvesting practises. Proton loads promote weathering, base cation exchange, and aluminium mobilisation, but the response and kinetics may depend on soil properties. Rapid reactions are ion exchange, dissolution of soluble salts and poorly ordered oxides, whereas slow and very slow reactions are dissolution of easily weatherable minerals and more or less poorly ordered oxides (Raulund-Rasmussen *et al.*, 1996). A method proposed by the same authors was used to characterise the capability for nutrient release and acid neutralisation at different time scales. Exchangeable cations and weathering products from dissolution of minerals were extracted in dilute (0.1 M) nitric acid in three consecutive steps for 2 hours, 48 hours and 168 hours, in total 218 hours of extraction (paper VI). The element release to pools separated by extractions was expected to reflect the reactivity of minerals present in the soil samples. Rates of element release have characteristic patterns of decline with extraction time. Changing release rates may correspond with exhaustion of element pools with different reactivity. Thereby, element release in consecutive extractions will reflect properties of the mineral assembly.

19 Danish forest soil profiles were described and characterised by physical and chemical analyses of pH, exchangeable cations, and soil texture (paper VI), and assigned to a texture class according to Table 1. The amount of nutrients extracted in genetic soil horizons to a soil volume of 100 cm soil depth characterised the nutrient release capability in rapid (0 - 2 hour), slow (2 - 50 hour) and very slow (50 - 218 hour) pools (Table 5). The texture classification explained 81% to 85% of variation in base cation release. The three pools that were separated by repeated extraction ranged from 2 to 4 $mol_+ m^{-2}$ in coarse soils, from 6.5 to 11 $mol_+ m^{-2}$ in medium soils, and from 42 to 102 $mol_+ m^{-2}$ in fine textured soils. Phosphorus pools were less well described by texture class, which was probably due to phosphorus fertilisation during previous agricultural use. Phosphorus fertilisation affects mineral soil phosphorus pools for long time periods (Fransson & Bergkvist, 2000).

Table 5. *Base cation (BC) release and phosphorus (P) pools in repeated extractions representing rapid (0-2 h), slow (2 - 50 h) and very slow (50-218 h) nutrient release, 0-100 cm soil depth (paper VI, Table 2 and 4). N~number of profiles. Significant differences within each column indicated by lowercase letters, P<0.05.*

Texture class	N	BC 0 - 2 h	BC 2 - 50 h	BC 50 - 218 h	P 0 - 2 h	P 2 – 50 h	P 50 - 218 h
		$mol_+ m^{-2}$			$g m^{-2}$		
Coarse	3	2.6^b	2^c	4^c	8^b	3^b	2^b
Medium	4	6.5^b	9^b	11^b	34^a	20^a	8^{ab}
Fine	11	102^a	42^a	54^a	60^a	30^a	24^a

Released pools of base cations (Ca, Mg, and K) relative to the sum of cations (base cations + aluminium) to 100 cm soil depth were termed base index. The base index revealed differences between texture classes (Table 6). Coarse textured soils had large rapidly reacting pools of aluminium relative to sum of cations, yielding a base index of 0.03, which was increased during extractions to 0.10 in very slowly reacting pools. In medium textured soils the base index increased from 0.07 to 0.21.

Table 6. *Base index (BI) in three base cation pools separated by consecutive 0.1 M HNO_3 extractions for 2 h, 2 – 50 h and 50 – 218 h, 0-100 cm soil depth. Significant differences in each column indicated by lower-case letters. P <0.05.*

Texture class	BI 0 - 2 h	BI 2 - 50 h	BI 50 - 218 h
Coarse	0.03^{b*}	0.03^{c}	0.10^{b}
Medium	0.07^{b}	0.14^{b}	0.21^{a}
Fine	0.39^{a}	0.21^{a}	0.24^{a}

* p-value coarse vs- medium 0.055.

The morphology of coarse and medium textured soil profiles revealed signs of podsolisation, i.e. accumulation of carbon and/or sesquioxides in Bh, Bhs and Bs horizons in soils with increasing base index in rapid, slow and very slow pools (see profile descriptions in Appendix I). The aluminium release decreased from the first to the last step, indicating a fast reaction of aluminium release from reactive aluminium compounds (*paper VI, Figure 4*). Mulder *et al.* (1989) concluded that proton loads to acid soils might reduce and even deplete reactive aluminium in organic complexes as a source of strong acid neutralisation.

Base index in fine textured soils decreased from an estimate of 0.39 in the rapid pool to 0.24 in the very slowly reacting pool (*paper VI, Table 4*). The decline was not tested statistically. Soils with decreasing base index were characterised by accumulation of base cations in fast reacting pools relative to the long-term index that reflects mineralogical properties of slowly reacting minerals. The relative accumulation of rapidly reacting (exchangeable) base cations may be an effect of base pumping activity by roots. Continuous litter inputs to surface layers and incorporation into mineral soil by macrofauna lead to mull formation. During the Holocene, continuous leaching of these soils has not removed base cations at the rate they have been released, thus leading to podsolisation; apparently the nutrient release by weathering has more than balanced uptake and leaching.

The method of repeated dilute nitric acid extraction revealed a differentiation of texture classes in respect of nutrient release capability in a short-term and long-term perspective. This supports the applicability of texture class as a general transfer function for long-term soil fertility. In fine textured soils, dissolution of calcium carbonate, acidification and clay eluviation have formed Alfisols. The Frijsenborg profile showed a more advanced stage of acidification, since it was a podsolised fine textured soil with a Bt horizon, and a calcium carbonate front in 2 m soil depth. In profiles where this front was within or around 1m soil depth, subsoil pH in soil depth 50-100 cm was nonacid, i.e. higher than 5 (*paper VI, Table 1*). Strongly leached, acid, fine-textured soils deserve closer investigation.

The method does not provide any estimate of annual weathering rates, but describes the dynamic properties of different texture classes relative to each other. In comparison to mineralogical analyses like X-ray diffraction and total chemical analysis the method provides information that may be interpreted in relation to nutrient release kinetics. The amount of nutrients released, the base index, and the pattern of change during three extractions, suggest that the texture classes reflect differences in mineralogy that govern soil development and nutrient availability. Texture class is thereby a transfer function for long-term nutrient supply.

10. TRANSFER FUNCTIONS AND INDICATORS OF FOREST SOIL QUALITY

10.1 Soil quality

Relationships between driving variables and ecosystem properties (Figure 1) may be seen as quantitative assessments of forest soil quality. Soil quality is ”the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Anon., 2002b).” Indicators of e.g. nitrate leaching at site level must fulfil a suite of requirements. A good indicator i) is linked to the ecological function in question, ii) is responsive to the assessment question, iii) provides information useful to a management decision, iv) preferably contributes information to multiple assessment questions at different spatial scales, and v) is cost effective (Jackson *et al.*, 2000). Indicators of three such qualities: carbon sequestration, nitrate leaching, and soil fertility are discussed in the following.

10.2 Indicators of carbon sequestration

Maintaining current soil carbon pools and increasing soil carbon pools has become a desired quality of forest soils in the attempt to sequester emitted carbon dioxide. Indicators should be focused on pools, where changes can be expected in the short term. Carbon sequestration in biomass may roughly be predicted the by the site quality for growth for different tree species (paper I). Growing conifers with high growth rates that develop thick organic layers could be an optimising strategy for carbon sequestration on coarse and medium textured soils. Such a strategy may conflict with preservation of the soil nutrient capital, because the very limited soil base cation pools would be decreased, and the capability of replenishment by weathering is low (paper VI).

Mineral soil carbon can be estimated from the type of master horizon, horizon thickness and subordinate horizon type. Such data are recorded in field surveys. Master horizons had significantly different carbon concentrations (O, A, E, B and C). Subordinate B horizon designations for accumulation of humus (h), sesquioxides (s), weathering products (w) or clay (t) similarly had different concentrations (*Vejre et al., 2003, Table 4*). Carbon concentrations and horizon thickness may both be climate dependent, yielding the highly different estimates of carbon pools observed along the climate gradient. It was not investigated using the present data, but Tamm (1950) states that the thick, humus rich Bh and Bhs horizons that hold large amounts of carbon in coarse and medium textured soils in Denmark are not a feature of boreal podsolised soils.

Nutrient-rich, well-drained soils apparently cycle litter at a rate that prevents accumulation of thick forest floors. Including the forest floor, total soil carbon did not increase 29 years after afforestation on nutrient rich loamy, calcareous soils (Vesterdal *et al.*, 2002). In the mineral soil, soil carbon tended to decrease. However, a changed distribution of soil carbon to the uppermost part of the former plough layer was observed (Vesterdal *et al.* op. cit.). In nutrient rich soils, sequestered carbon would thus be stored in live biomass rather than as organic matter in decomposing forest floors, and here the growth rate of different tree species as related to soil fertility (e.g. paper I) would be an important indicator of carbon sequestration.

The present study was focused on properties of well-drained soils, whereas hydromorphic soils, not to speak of organic soils, have hardly been dealt with. Processes like denitrification and methane production by bacteria in anaerobic environments are central. Ditching and other changes in hydrology may change forest soils into sources or sinks for carbon (and N). A lowered water table may cause CO_2 release to the atmosphere and nitrate leaching to groundwater due to net mineralisation of organic material. Such a case was observed in the national survey of nitrate leaching (*Callesen et al. 1999, Figure 3 case A2*).

Soil carbon pools may be estimated from soil morphology and transfer functions as presented here, whereas sequestration may be studied in chronosequences on different soil types as done by Vesterdal *et al.* (op. cit.) on nutrient rich soils.

10.3 Indicators of nitrate leaching

Nitrate leaching is associated with decoupled nitrogen cycling in the forest ecosystem. Datasets of more than 100 plot and catchment studies where internal and external nitrogen fluxes have been determined have been used to identify indicators of nitrate leaching. Leaching of nitrate is related to the amount of through-fall nitrogen deposition to forest soils (Macdonald *et al.*, 2002; Kristensen *et al.*, in press). These analyses comprise plot and catchment studies across Europe, and therefore also probably reflect gradients in soil nitrogen pools, C:N ratios and nitrogen deposition that are correlated with climate as demonstrated in paper IV. For the same level of elevated through-fall nitrogen of 10 kg N ha^{-1} y^{-1}, Kristensen *et al.* (2002) find that broadleaves have higher nitrate concentrations in soil leachate than conifers. They attribute the finding to confounding factors in the data: broadleaves are probably located on more fertile soils. Macdonald *et al*. (2002) use C:N ratio of the organic layer to distinguish the nitrate leaching response to annual nitrogen through-fall in the range 0 to 60 kg N ha^{-1} y^{-1} of mainly coniferous sites on acid soils. At an annual input of 30 kg N ha^{-1} y^{-1}, sites with C:N ratios below 25 leach on average 15 kg N ha^{-1} y^{-1} in contrast to sites with C:N>25 that leach 9 kg N ha^{-1} y^{-1}. Leaching is highest at a pH below 4.6, but whether the acid status is an effect of leaching or inherent properties of the soils is unclear. It may be a confounding of e.g. geological origin and nitrogen deposition regime. This classification of C:N ratios indirectly accounts for temperature climate and nitrogen deposition regime. In fact, boreal sites that are limited by nitrogen and temperature climate should be excluded from such analyses, since excess nitrate and thus leaching is not an issue at boreal sites in low deposition areas (Binkley & Högberg, 1997). It is more important to investigate the nitrogen status, and the ability to nitrify shown as net nitrification at sites with comparable climate and nitrogen deposition regimes.

Andersson *et al.* (2002) states the importance of current nitrogen deposition, earlier nitrogen additions and soil nitrogen status to the annual soil nitrogen flux density (net mineralisation + nitrogen deposition). Leaching of nitrate is seen at sites with soil nitrogen flux densities above 90 kg ha^{-1} y^{-1}, and the leaching is inversely related to C:N ratio in the organic layer that range from 27 to 39.

C:N ratio of the forest floor has been suggested as an indicator of nitrogen leaching based on regressions of nitrogen status parameters across climate zones (e.g. Gundersen *et al.*, 1998; Macdonald *et al.*, 2002; Andersson *et al.*, 2002). In fact, such regressions reveal that boreal coniferous forests in cold climate at background deposition have high C:N ratios, low nitrogen pools and no nitrate leaching. In contrast nitrogen retention in forests of the nemoral zone may depend on stand age (relative uptake capacity for N), deposition regime in combination with crown filter capacity as determined by tree type (conifer/broadleaved), nitrogen status of the soil, and previous land use. This data would be valuable in prediction of nitrogen leaching risk in case of disturbance. Multivariate analyses such as PCA would reveal some of the confounding effects that blur interpretations of data from plot and catchment studies across environmental gradients.

With the results of soil texture class, climate and soil depth relationships with C:N ratio demonstrated in paper IV, use of C:N ratio as an indicator for nitrate leaching is now with the reservation, that these effects should be accounted for as well. Analyses of genetic soil horizons (*Vejre et al., 2003, Figure II*) and C:N ratios versus soil depth (Figure 11) suggest that mineral soil C:N ratio in the upper 10 or 15 cm mineral soil may be more suitable than the C:N ratio of the organic layer, since it is more independent of litter type. On fertile sites the litter may mineralise completely, and the information will be lacking, whereas carbon and nitrogen measurements in topsoils are available in most soil databases.

Indicators based on sampling and measurement are more expensive than those based on field observation. In Denmark subsoil texture class and soil pH would be less expensive than C:N ratio in predicting the probability of net nitrification, which is a precondition for nitrate leaching. C:N ratio may be a valid indicator of nitrogen enrichment and nitrate leaching risk in coniferous forests in high nitrogen deposition areas. However, the inherent nitrogen status of a site can be inferred from climate, texture class, deposition regime and land use history. For nitrogen leaching risk assessment, nitrogen deposition regime, subsoil texture class and subsoil reaction are therefore recommended as indicators.

10.4 Indicators of soil fertility

Soil fertility is one aspect of soil quality, namely ”the quality of a soil that enables it to provide nutrients in adequate amounts and in proper balance for the growth of specified plants or crops” (Anon, 2002b). Exchangeable soil nutrient pools calculated in fixed soil volumes, expressed as depth gradients or for root depths specific to tree species are common indicators of nutrient reserves (Rehfuess, 1999). Tree species respond differently to nutrient availability (paper I). Assessed by volume growth, soil fertility is not a general quality of the soil, but dependent on tree species. As an example, sandy soils would be more fertile to conifers than to broadleaves. Soil fertility rated by growth of trees is relative and ambiguous.

Nitrogen availability is indicative for soil fertility, provided that other nutrients are not in deficit (Schoenholtz *et al.* 2000). Total C:N ratios in the soil profile are correlated with subsoil properties like extractable phosphorus and clay content (*Vejre et al., 2003, Table 6*), which are also correlated with tree growth in Denmark (Figure 7 and *paper I, Table 2*). Low C:N ratios reflect high nitrogen pools in base-rich Alfisols. C:N ratio may thus be used as an indicator of soil fertility. However, effects of chronic nitrogen deposition are observed as decreased C:N ratios in forest floors (Prietzel *et al.*, 1997). Therefore, low C:N ratios may not be indicative for a fertile subsoil. As a consequence, C:N ratio is no longer a general indicator of soil fertility. Subsoil texture class and the presence of calcium carbonate in the parent material as determined in field surveys are not prone to changes from air pollution in the short term of decades. These properties are suggested as more robust indicators of soil fertility than C:N ratios.

An ecological site classification developed for British forests is based on investigations of ground vegetation, humus type and soil chemistry at seventy sites across seven climate zones from warm and dry to alpine (Wilson *et al.*, 2001). The soil fertility rating into classes of soil nutrient regime is intended for a multitude of forest management purposes, e.g. choice of tree species. N-availability and nitrification before and after incubation, soil pH, and nutrient pools to 50 cm soil depth are analysed in relation to ground flora indicator species for nitrogen availability and soil reaction by multivariate analysis (canonical correlation). The soil variables in the UK study are correlated, and the sites are classified numerically into five nutrient regimes. The use of humus form and ground flora as indicators across a wide climatic range may introduce bias from soil-climate interaction and historical land use. E.g. a mor-type humus could have been formed either due to cold climate or nutrient poor substrate. At recently afforested sites or in dense spruce plantations, the soil parameters would have to apply as indicators in the absence of flora. The most important chemical properties distinguishing sites are nitrate availability and soil pH (Wilson *et al.*, 2001). Disturbed nitrogen cycling causing vegetation changes and soil acidification may complicate the use of ground flora, humus form and pH in top soils in soil fertility rating, since they are indicators of ecosystem state factors rather than driving variables of soil development (cf. Figure 1).

Subsoil texture classes coarse, medium and fine, and subsoil pH were used to distinguish six soil nutrient regimes, based on 19 Danish forest soil profiles (*paper VI*). Two classes of poor soils have coarse texture class, acid subsoil soil reaction and acid mineralogy, i.e. a base index of 0.10 - 0.15, and a phosphorus release of less than 20 g m^{-2} (very poor) or 20 - 50 g m^{-2} (poor). Medium poor and medium rich soils are medium or fine textured with acid subsoil reaction, and a long-term base index in the range 0.15 - 0.25. The two classes of rich soils are fine textured with a subsoil reaction above 5, and a long-term base index around 0.25 (*paper VI, Table 5*). Nutrient pools of base cations and phosphorus calculated to 1m soil depth are correlated with pH, and closely related to texture class in this classification system.

The actual soil volume in contact with roots may be very limited compared to estimated root depths. Nutrient budgets calculated for Southern Sweden use soil depths specific to tree species, e.g. 0.35m in spruce, 0.45m in pine and 0.65m in broadleaves (Sverdrup, 2002). Thereby, broadleaved species with a deep root system are favoured by almost doubling available soil nutrient reserves in broadleaved forest, and thus the site capacity for these species determined by estimated weathering inputs of this larger soil volume. It should be highlighted in any discussion of site carrying capacity that is based on such nutrient budgets, since the assessment is tree species dependent.

The transfer functions for carbon and nutrient characteristics are valid for well-drained forest soils in the study region. Application of the texture classification outside Denmark, e.g. in the Nordic countries may reveal that mineralogy and texture class are not confounded, contrary to what seems to be the case in Denmark.

Texture class and pH are obtainable in a field survey, whereas nutrient pools require sampling and analysis in the laboratory. Texture class and pH would be more cost-effective indicators of soil fertility than analyses of properties of the exchange complex or the mineral phase.

Maintenance of forest soil fertility is subject to monitoring as part of European forest policy, since forests are under pressure from acidifying air pollution[1]. Monomeric aluminium in soil solution has been studied in forest health research as a potentially phytotoxic ion preventing nutrient uptake. Negative effects of monomeric aluminium have been demonstrated in hydroculture (Cronan & Grigal, 1995), but unambiguous evidence is difficult to obtain from e.g. spruce forest ecosystems that are adapted to nutrient poor and acid conditions. One explanation could be that mycorrhizas may short cut nutrient uptake from soil solution, thereby diminishing the potential harmful effect of monomeric Al (van Breemen *et al.*, 2000). Mobilisation of aluminium in response to acidification is the background for the monitoring of decreasing base saturation and calcium:aluminium ratios in soil solution, plant tissue, and on the soil exchange complex (Sverdrup *et al.*, 1992; Cronan & Grigal, 1995). Time series recorded in the 1980s and 1990s reveal that mobilisation of monomeric aluminium is related to influx of nitrogen and sulphur (Hovmand & Bille-Hansen, 1999). Following a gradual decline in sulphur deposition since the 1980s, a decline in organic and inorganic monomeric aluminium concentrations in run-off has been reported in the Hubbard Brook Experimental Forest, in north eastern USA (Palmer & Driscoll, 2002). These examples of soil water monitoring have demonstrated how air pollution affects soil water chemistry.

Soil solution pH is the distinguishing feature in the ecological soil classification system suggested by Ulrich (1981). Buffer ranges of carbonate/carbonic acid (pH 6.2 to 8.6), carbonic acid/silicates (pH 5 to 6.2), exchange complex (4.2 to 5), aluminium buffer (2.8 to 4.2), and iron buffer (pH 2.4 to 3.8) are outlined along with characteristics of the base saturation of the exchange complex. Soil pH controls a range of processes including nutrient availability. The study by Ulrich (op. cit.) underlines that pH, together with soil texture, may be seen as master variables of forest soil fertility.

Base saturation in forest soils is an indicator that is currently monitored in the ICP forest framework, Level I (Vanmechelen *et al.*, 1997). Changes in base saturation are not synonymous with a loss of base cations from the ecosystem, but may signify a temporal redistribution to living biomass or to the forest floor. Decline in base saturation over a 10 year period reflects two points in stand development that might as well reflect increases in living biomass and soil organic matter. In aggrading stands, base cations are transferred from soils to biomass (Knoepp & Swank, 1994). If monitoring programmes do not reflect all phases of the forest stand cycle including

[1]Third Ministerial Conference on the Protection of Forests in Europe 2-4 June 1998, resolution L2

phases with net mineralisation of organic matter after clear-cutting, the evaluation of the assessment question in the monitoring programme will be biased. However, the periodic measurement of acidity and the change over time may be used to evaluate the need for countermeasure programmes such as liming, and later on, to monitor the effects of liming. Large-scale liming programmes in Germany have been used to counteract effects of acidifying air pollution to forest ecosystems in the 1980s and 1990s, e.g. in Nordrhein-Westphalen[2].

The cited definition of soil fertility applied to forest ecosystems is inadequate, because forest stands differ from annual crops by the longevity of the forest stand allowing internal redistribution of nutrients. Biogeochemical cycling of nutrients in forest ecosystems is a more appropriate framework for the evaluation of soil fertility. However, quantification of all nutrient fluxes is tedious. By estimating external fluxes of base cations and nitrogen fluxes in input-output budgets, enrichment or depletion of these nutrients can be monitored. Element budgets have been suggested as management tools for monitoring of nutrient management (Ranger & Turpault, 1999). Estimates of e.g. base cation deposition and weathering inputs involve uncertainty of 50% for base cation deposition and maybe more for weathering inputs (Sverdrup 2002). As a consequence, book keeping systems at site level for nutrient inputs and outputs may be used to increase the awareness of the fact that some forest operations may induce nutrient losses.

However, the cumulative error disables the evaluation of nutrient depletion in nutrient budgets, since confidence limits would be wide. Nutrient balances could include positive and negative values indicating enrichment or depletion, and thereby offer no decision aid for e.g. the need for compensatory fertilisation with base cations. At site level, monitoring of soil chemical variables for long-term soil fertility is not relevant, since nutrient cycling in forest ecosystems is too complex and changes are too difficult to detect. A measured value of e.g. topsoil pH or base saturation is not likely to offer decision aid at site level, unless target levels for e.g. base saturation or soil pH are imposed by political decision. In contrast, the long-term soil nutrient regime based on subsoil texture class and subsoil reaction is valuable information at site level.

11. CONCLUSIONS AND PERSPECTIVES

The model of soil and ecosystem development that distinguished driving variables, state and function (Figure 1) proved to be a meaningful concept for establishment of transfer functions for environmental benefits. Subsoil

[2] Ministerium für Umwelt und Forsten Rheinland-Pfalz (1998). 10 Jahre erfolgreiche Bodenschutzkalkung in den Rheinlandpfälzischen Wäldern.

texture either in the form of numerical variables or as a class variable integrated soil qualities as tree growth, the size and vertical distribution of carbon and nitrogen pools, nitrogen transformation in soils and nitrate leaching, and long-term nutrient release capability. This is trivial old knowledge, but the simplicity of the texture classification and the quantitative description by extensive data sets is new common ground.

Three texture classes as proxies for parent material; mean annual temperature and mean annual precipitation could describe accumulation of carbon and nitrogen quantitatively. The positive trends with temperature contradicted global trends, probably a result of using only well-drained soils in a regional study. The precision of estimates based on the relationships did not suggest that these parameters should be used to predict carbon and nitrogen pools, but at least a regional estimate of current carbon and nitrogen pools in well-drained soils is now available. Transfer functions for carbon and nitrogen concentrations based on master horizons are more useful.

As a general conclusion, growth-soil-site studies, carbon sequestration studies, N-retention studies, and acidification studies in forests should take basic soil properties like subsoil texture and also subsoil acidity (pH) into account. The importance of stratification into homogeneous soil and climate units prior to meta-analysis of results from process studies in forest soils has now been emphasised. For the same reason, the suggested classification system of soil nutrient regimes in Danish forest soils is based on long-term properties and linked to soil texture classes and subsoil pH. The release of base cations, the base index and the pattern of cation release to three pools by the soil test method applied were related to texture class.

The relative robustness of forest soils to applied stresses increase in the order coarse, medium and fine. Nitrate availability and nitrate leaching exhibit fundamental differences related to texture class and soil nutrient availability that coincide with nutrient release capability of the soil mineral phase. In consequence, soils that currently nitrify and leach nitrate are also robust in the sense that they have nutrient reserves to counteract the base cation loss.

Other texture classifications may apply in regions with different geology and geomorphology. The applicability of the texture transfer function should be tested in other regions of newly glaciated soils.

Cause-effect relationships may be speculated, but not concluded from empirical correlation between ecosystem characteristics across environmental gradients. Trends observed in ecological records may give rise to new hypotheses, and inspire designed experiments from which causal relationships could be tested, or encourage additional sampling to complete or extend existing datasets. Here, it is concluded that crossed datasets of sites in respect of soil nutrient status, climate, N-deposition, and tree species would overcome the problem of confounded factors like e.g. nitrogen deposition and temperature; and could be an object for future studies.

12. ACKNOWLEDGEMENTS

I owe warm thanks and gratitude to my supervisors Karsten Raulund-Rasmussen and J. Bo Larsen for initiating the project, for ideas and encouragement during the project. Thanks to inspiring and cheerful colleagues at The Danish Forest and Landscape Institute for sharing and discussing ideas in a stimulating atmosphere. I also thank Co-operation partners Mogens H. Greve and Finn Plauborg Hansen at Danmarks Jordbrugsforskning for access to national soil databases and to climate data.

During December-January 2000-2001 Docent Ingrid Stjernquist and Professor Bengt Nihlgaard kindly adopted me in the Forest Ecology research group at the University of Lund. Thanks to everyone in the department for introducing me to the work in your group and for good coffee breaks. Lastly, I am thankful to family and friends who supported and encouraged my work and listened patiently.

The study was financed by The Danish Forest and Landscape Research Institute, Forskerakademiet, Aage V. Jensens Fonde, The Danish Forest and Nature Agency, The Danish Environmental Research Programme *Foranderlige Landskaber*, and the Quality of Life Programme (FP5) QLK5-CT-2001-00527.

Copenhagen, July 15, 2003.

13. REFERENCES

Andersen,M.K., Raulund-Rasmussen,K., Hansen,H.C.B., Strobel,B.W., 2002. Distribution and fractionation of heavy metals in pairs of arable and afforested soils in Denmark. Eur. J. Soil Sci. 53, 491-502.

Andersson,P., Berggren,D., Nilsson,I., 2002. Indices for nitrogen status and nitrate leaching from Norway spruce (Picea abies (L.) Karst.) stands in Sweden. For. Ecol. Manag. 157, 39-53.

Anon. 1998. World reference base for soil resources. Deckers, S., Spaargaren, O. C., and Nachtergaele, F. O. (Ed.) World soil resources reports no. 84. Rome, FAO, ISRIC and ISSS.

Anon. 2002a. Skove og Plantager. Larsen, P. H. and Johannsen, V. K. (Ed.). København, Danmarks Statistik, Skov & Landskab, Skov- og Naturstyrelsen. 171 p.

Anon. 2002b. The Glossary of Soil Science Terms. The Soil Science Society of America. http://www.soils.org/sssagloss/, July 2003.

Arrhenius,O. 1934. Fosfathalten i skånska jordar. Sveriges geologiske undersökning serie C Årsbok 28, 4-32. Stockholm, Kungl. Boktryckeriet. P.A. Norstedt & Söner.

Augusto,L., Ranger,J., Binkley,D., Rothe,A., 2002. Impact of several common tree species of European temperate forests on soil fertility. Annals of Forest Science 59, 233-253.

Barnes,B.V., Zak,D.R., Denton,S.R., Spurr,S.H., 1998. Site quality and ecosystem evaluation. In: Forest ecology. Wiley & Sons, New York, pp. 298-329.

Beier,C., Gundersen,P., 1989. Atmospheric deposition to the edge of a spruce forest in Denmark. Environm. Pollut. 60, 257-272.

Binkley,D., Giardina,C., 1998. Why do tree species affect soils ? The warp and woof of tree-soil interactions. Biogeochem. 42, 89-106.

Binkley,D., Högberg,P., 1997. Does atmospheric deposition of nitrogen threaten Swedish forests. For. Ecol. Manag. 92, 119-152.

Bornebusch,H.C., 1933. Hedeskovens foryngelsen. III. Dybtgaaende jordbundsundersøgelser. Det Forstlige Forsøgsvæsen,Danmark 13, 1-50.

Bradshaw,R., Holmqvist,B.H., 2000. Danish forest development during the last 3000 years reconstructed from regional pollen data. Ecography 22, 53-62.

Breuning Madsen,H., Jensen,N.H. 1985. Jordprofilundersøgelsen. Rapport over pedologiske studier udført i forbindelse med anlæg af hovedtransmissionsledninger for naturgas i Danmark. Landbrugsministeriet, Arealdatakontoret. pp. 1-47.

Breuning Madsen,H., Nørr,A.H., Holst,Kr.Aa. 1992. Den danske Jordklassificering. Atlas over Danmark. [Serie 1, bind 3]. København, Det kongelige danske geografiske selskab.

Breuning Madsen,H., Olsson,M. 1995. Jordbundsundersøgelser i EUs kvadratnet for monitering af skovsundhed, Danmark. København, Geografisk Institut, Københavns Universitet. pp. 5-15.

Breuning Madsen,H., Platou,S.W., 1983. Land use planning in Denmark. The use of soil physical data in irrigation planning. Nord. Hydro. 267-276.

Buol,S.W., Hole,F.D., McCracken,R.J., Southard,R.J., 1997. Soil genesis and classification. Iowa State University Pres, Ames, Iowa.

Carmean,W.H., 1975. Forest site quality evaluation in the United States. Advances in Agronomy 27, 209-269.

Carmean,W.H., Li,J., 1998. Soil-site relations for trembling aspen in Northwest Ontario. North. J. Appl. For. 15, 146-153.

Cronan,C.S., Grigal,D.F., 1995. Use of Calcium/Aluminium ratios as indicators of stress in forest ecosystems. J. Environ. Qual. 24, 209-226.

de Wit,H.A., Kvindesland,S. 1999. Carbon stocks in Norwegian forest soils and effects of forest management on carbon storage. Rapport fra skogforskningen. 14, 1-52. Ås, Norway, NLH, NISK.

Falkengren-Grerup,U., Linnermark,N., Tyler,G., 1987. Changes in acidity and cation pools of south Swedish soils between 1945 and 1985. Chemosphere 16, 2239-2248.

FAO (1990). Guidelines for soil profile description. 3rd Ed. Soil Resources, Management and Conservation Service. Land and Water Development Division. Rome. 69 p.

Fisher,R.F., Binkley,D., 2000. Ecology and management of forest soils. John Wiley and Sons, Inc., New York.

Fog,K., 1988. The effect of added nitrogen on the rate of decomposition of organic matter. Biol. Rev. 63, 433-462.

Fransson,A., Bergkvist,B., 2000. Phosphorus fertilisation causes durable enhancement of phosphorus concentrations in forest soil. For. Ecol. Manag. 130, 69-76.

Grigal,D.F., Ohmann,L.F., 1992. Carbon storage in upland forests of The Lake States. Soil Sci. Soc. Am. J. 56, 935-943.

Greve, M.H., Sørensen, P., (1992) Vejledning i jordprofilbeskrivelse. Geokompendium nr. 30. Geologisk Institut, Aarhus Universitet.

Gundersen,P., Callesen,I., de Vries,W., 1998. Nitrate leaching in forest ecosystems is related to forest floor C/N ratios. Environm. Pollut. 102, 403-407.

Gundersen,P., Schmidt,I.K., Raulund-Rasmussen,K.. Leaching of nitrogen from temperate forests - effects of air pollution and forest management. In: Vertessy,R., Elsenbeer,H. (Eds.), Forests and Water, *in press*. IUFRO.

Hansen,S., 1965. The Quarternary. In: Rankama,K. (Ed.)., The Quarternary. Interscience Publishers, New York.
Hägglund,B., Lundmark,J.-E. 1977. Site index estimation by means of site properties. Scots pine and Norway spruce in Sweden. Report 138, 5-38. Stockholm, Swedish College of Forestry.
Holdridge, 1947. Determination of world plant formations from simple climatic data. Science 105, 367 - 368.
Holmsgaard,E., Bang,C., 1977. Et træartsforsøg med nåletræer, bøg og eg; de første 10 år. (A species trial with conifers, beech and oak; the first ten years). Det Forstlige Forsøgsvæsen, Danmark 35, 159-196.
Homann,P.S., Sollins,P., Chappell,H.N., Stangenberger,A.G., 1995. Soil organic matter in a mountainous, forested region: Relation to site characteristics. Soil Sci. Soc. Am. J. 59, 1468-1475.
Hovmand,M.F., Bille-Hansen,J., 1999. Atmospheric input to Danish spruce forests and effects in soil acidification and forest growth based on 12 years measurements. Water, Air, Soil Pollut. 116, 75-88.
Jackson,L.E., Kurtz,J.C., Fischer,W.S. 2000. Evaluation guidelines for ecological indicators. EPA/620/R-99/005, p. 1-6. NC, U.S. Environmental Protection Agency, Office for Research and Development, Research Triangle Park.
Jenny,H., 1980. The soil resource. Springer-Verlag, New York Heidelberg Berlin.
Jobbágy,E., Jackson,R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological applications 10, 423-436.
Jönsson,U., Rosengren,U., Thelin,G., Nihlgard,B (2003). Acidification-induced chemical changes in coniferous forest soils in southern Sweden 1988-1999. Env. Pollut. 123: 75-83.
Kabzems,R.D., Klinka,K., 1987a. Initial quantitative characterization of soil nutrient regimes. I. Soil properties. Can. J. For. Res. 17, 1557-1564.
Kabzems,R.D., Klinka,K., 1987b. Initial quantitative characterization of soil nutrient regimes. II. Relationships among soils, vegetation, and site index. Can. J. For. Res. 17, 1565-1571.
Knoepp,J.D., Swank,W.T., 1994. Long-term soil chemistry changes in an aggrading forest ecosystem. Soil Sci. Soc. Am. J. 58, 325-331.
Köhler,H.. Untersuchungen über die Beziehungen zwischen Standortfaktoren, Ernährungszustand und Wachstum von Fichten (*Picea abies (L)* Karst.) der Herkunft Westerhof auf Verschiedenen Standorten Niedersachsens.1984. Forstlichen Fakultät, Georgia-Augusta-Universität Göttingen. Ph.D. thesis. 251 p.
Kristensen,H.L., Gundersen,P., Callesen,I., Reinds,G.J. Troughfall N deposition influences soil solution nitrate concentration differently in European coniferous and deciduous forests. Ecosystems, *in press*.

Krogh,L., Breuning-Madsen,H., Greve,M.H., 2000. Cation-exchange capacity pedotransfer functions for Danish soils. Acta Agricultura Scandinavica, Sect. B, Soil and plant sci. 50, 1-12.

Leary,R.A., Johannsen,V.K., Förster,W., Tarp-Johansen,M.J., Skovsgaard,J.P. A difference equation parameter as an indicator of site quality for Norway spruce in Denmark. *In review*.

Macdonald,J.A., Dise,N.B., Matzner,E., Armbruster,M., Gundersen,P., Forsius,M., 2002. Nitrogen input together with ecosystem nitrogen enrichment predict nitrate leaching from European forests. Global change biology 8, 1-6.

Magnussen,S., 1983. En tilvækstoversigt for rødgran på østersønære lerede morænejorder. Dansk Skovfor. Tidsk. 215-246.

Marschner,H., 1986. Mineral nutrition of higher plants. Academic Press Limited, London.

Mulder,J., van Breemen,N., Eijck,H.C., 1989. Depletion of soil aluminium by acid deposition and implications for acid neutralization. Nature 337, 247-249.

Nadelhoffer,K.J., Emmett,B.A., Gundersen,P., Kjønaas,O.J., Koopmans,C.J., Schleppi,P., Tietema,A., Wright,R.F., 1999. Nitrogen deposition makes a minor contribution to carbon sequestration in temperate forests. Nature 398, 145-148.

Nellemann,C., Goul Thomsen,M., 2001. Long-term changes in forest growth: potential effects of nitrogen deposition and acidification. Water, Air, Soil Pollut. 197-205.

Nihlgård,B., 1985. The ammonium hypothesis - An additional explanation to the forest dieback in Europe. Ambio 14, 2-8.

Oades,J.M., 1988. The retention of organic matter in soils. Biogeochem 5, 35-70.

Palmer,S.M., Driscoll,C.T., 2002. Decline in mobilization of toxic Aluminium. Nature 417, 242-243.

Påhlsson,L., Abrahamsen,J., Dahl,E., Kingo Jacobsen,N., Kalliola,R., Vilborg,L., 1984. Naturgeografisk regionindelning av Norden. Nordiska Ministerrådet.

Pedersen,L.B., Bille-Hansen,J., 1995. Historisk udvikling i jordforsuring i danske skove. Skoven 27, 344-348.

Persson,T., Karlsson,P., Seyferth,U., Sjöberg,R.M., Rudebeck,A., 2000. Carbon mineralisation in European forest soils. In: Schultze,E.-D. (Ed.)., Carbon and nitrogen cycling in European forest ecosystems. Springer-Verlag, Berlin Heidelberg, pp. 257-275.

Persson,T., Rudebeck,A., Jussy,J.H., Colin-Belgrand,M., Priemé,A., Dambrine,E., Karlsson,P., Sjöberg,R.M., 2000. Soil nitrogen turnover - mineralisation, nitrification and denitrification in European forest soils.

In: Schultze,E.-D. (Ed.)., Carbon and nitrogen cycling in European forest ecosystems. Springer-Verlag, Berlin Heidelberg, pp. 297-331.
Post,W.M., Emanuel,W.R., Zinke,P.J., Stangenberger,A.G., 1982. Soil carbon pools and world life zones. Nature 298, 156-159.
Post,W.M., Pastor,J., Zinke,P.J., Stangenberger,A.G., 1985. Global patterns of soil nitrogen storage. Nature 317, 613-616.
Pretzsch,H., 1999. Changes in forest growth. Forstw. Cbl 118, 228-250.
Prietzel,J., Kolb,E., Rehfuess,K.E., 1997. Langzeituntersuchung ehemals streugenutzter Kiefernökosysteme in der Oberpfalz: Veränderungen von Bodenchemischen Eigenschaften und der Nährelemenversorgung der Bestände. Forstw. Cbl 116, 269-290.
Ranger,J., Turpault,M.-P., 1999. Input-output nutrient budgets as a diagnostic tool for sustainable forest management. For. Ecol. Manag. 122, 139-154.
Raulund-Rasmussen,K., Callesen,I. 1999. Nordsoil. Effekter af klimaændringer og luftforurening på nordiske skovøkosystemers carbon og nitrogenlagre, samt på skovenes produktionsevne. Hørsholm, Denmark, Danish Forest and Landscape Research Institute. Data file.
Raulund-Rasmussen,K., Dalsgård,M., Larsen,O.L., Borggaard,O.K. 1996. Development and application of a simple weatherability test. EU-report. Unpublished
Rehfuess,K.E., 1999. Indikatoren der Fruchtbarkeit von Waldböden - zeitliche Veränderungen und menschlicher Einfluss. Forstw. Cbl 118, 88-96.
Reich,P.B., Grigal,D.F., Aber,J.D., Gower,S.T., 1997. Nitrogen mineralisation and productivity in 50 hardwood and conifer stands on diverse soils. Ecology 335-347.
Scarascia-Mugnozza,G., Bauer G.A., Persson,H., Matteucci,G., Masci,A., 2000. Tree biomass, growth and nutrient pools. In: Schultze,E.-D. (Ed.)., Carbon and nitrogen cycling in European forest ecosystems. Springer-Verlag, Berlin Heidelberg, pp. 49-62.
Schoenholtz,S.H., van Miegroet,H., Burger,J.A., 2000. A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. For. Ecol. Manag. 138, 335-356.
Schulze,E.-D., 1989. Air pollution and forest decline in a spruce (Picea abies) forest. Science 244, 776-782.
Schwalm,C.R., Ek,A.R., 2001. Climate change and site: relevant mechanisms and modeling techniques. For. Ecol. Manag. 150, 241-257.
Seybold,C.A., Mausbach,M.J., Karlen,D.L., Rogers,H.H., 1998. Quantification of soil quality. In: Lal,R., Kimble,J.M., Follet,R.F., Stewart,B.A. (Eds.), Soil processes and the carbon cycle. CRC Press, Boca Raton, pp. 387-404.

Skeffington,R.A., Wilson,E.J., 1988. Excess nitrogen deposition: Issues for consideration. Environm. Pollut. 54, 159-184.
Soil Survey Division Staff, 1993. Soil survey manual. Handbook 18. http://www.statlab.iastate.edu/soils/ssm/gen_cont.html, Soil Conservation Service. U.S. Department of Agriculture.
Soil Survey Staff,U.S.D.o.A., 1992. Keys to Soil Taxonomy. Pocahontas Press, Inc., Blacksburg, virginia. 5th Ed.
Soil Survey Staff,U.S.D.o.A., 1998. Keys to soil taxonomy. Pocahontas Press, Inc., Blacksburg, virginia. 8th Ed.
Spiecker,H., 1999. Overview of recent growth trends in European forests. Water Air and Soil Pollution 116, 33-46.
Sverdrup,H., Warfvinge,P., Frogner,T., Håøya,A.O., Johansson,M., Andersen,B., 1992. Critical loads for forest soils in the Nordic countries. Ambio 21, 348-355.
Tamm,O., 1950. Northern coniferous forest soils. The scrivener press, Oxford.
Tamminen,P. 1993. Estimation of site index for Scots pine and Norway spruce stands in South Finland using site properties. Annila, E., Oja, S., and Salonen, T. Folia Forestalia 819, 1-26. Helsinki, The Finnish Forest Research Institute.
Tamminen,P., Starr,M., 1994. Bulk density of forested mineral soils. Scan. J. For. Res. 28, 53-60.
Ulrich,B., 1981. Ökologische Gruppierung von Böden nach ihrem chemischen Bodenzustand. Zeitschr. Pfl. Ern. Bodenk. 144, 289-305.
van Breemen,N., Mulder,J., Driscoll,C.T., 1983. Acidification and alkalinization of soils. Plant Soil 75, 283-308.
van Breemen, N., Finlay,R., Lundstrom,U., Jongmans,A.G., Giesler,R., Olsson,M., 2000. Mycorrhizal weathering: a true case of mineral plant nutrition? Biogeochem. 49, 53-67.
van der Salm,C. 1999. Weathering in forest soils. University of Amsterdam. Doctoral Dissertation, 287 p.
Vanmechelen,L., Groenemans,R., Van Ranst,E. 1997. Forest soil condition in Europe. Brussels, Geneva, Ministry of the Flemish Community, EC and UN/ECE. Technical Report. 257 p.
Vejre,H., Ingerslev,M., Raulund-Rasmussen,K., 2001. Fertilization of Danish forests: A review of experiments. Scandinavian Journal of Forest Research 16, 502-513.
Vesterdal,L., Ritter,E., Gundersen,P., 2002. Change in soil organic carbon following afforestation of former arable land. For. Ecol. Manag. 169, 137-147.
Vitousek,P.M., Aber,J.D., Howarth,R.W., Likens,G.E., Matson,P.A., Schindler,D.W., Schlesinger,W.H., Tilman,D.G., 1997. Human alteration

of the global nitrogen cycle: Sources and consequences. Ecological applications 7, 737-750.
Wardle,D.A., Zackrisson,O., Hörnberg,G., Gallet,C., 1997. The influence of island area on ecosystem properties. Science 277, 1296-1299.
Westman,C.J., Jauhiainen,S., 1998. Soil acidity in 1970 and 1989 in a coniferous forest in southwest Finland. Can. J. Soil Sci. 78, 477-479.
Wilson,S.M., Pyatt,D.G., Malcolm,D.C., Conolly,T., 2001. The use of ground vegetation and humus type as indicators of soil nutrient regime for an ecological site classification of British forests. For. Ecol. Manag. 140, 101-116.
Østergaard,H.S., Mamsen,P., 1990. Kvadratnet for nitratundersøgelser i Danmark, Oversigt 1986-1989. Landbrugets Rådgivningscenter, Landskontoret for Planteavl.

14. APPENDIX

I: Profilbeskrivelser (In Danish)

Most profiles have been described according to Greve & Sørensen (1992). Photos were taken by the person who described the soil profile if nothing else is indicated. Soil profiles at Lindet, Stenholts Vang and Ulborg were described according to an earlier edition of FAO (1990). Christianssæde and Holsteinsborg had no field description apart from horizon designations, and texture and humus classes are based on classes in Breuning Madsen et al., (1992). The profiles were classified according to Soil Taxonomy (1998), and World Reference Base (Anon., 1998).

For each profile described in Appendix I two tables with physical and chemical properties are presented in the following pages. Abbreviations are explained below. Analytical principles are described in the references. Profile data originating from earlier investigations are marked with a reference. "n.a." indicates that the assessment was not carried out.

Table I.a Abbreviations and methods used for physical and chemical soil analyses in Appendix I tables.

Name	Explanation	Reference and remarks
BD	Bulk density of the fine earth fraction (< 2 mm). Mass and volume of >2mm fraction deducted.	Undisturbed sample using 100 ccm containers. Blake & Hartge (1986)
clay silt fine sand coarse sand	0-2 µm (sedimentation) 2-20 µm (sedimentation) 20-200 µm (residual) 200-2000µm (sieving)	Particle size distribution of the fine earth fraction (< 2mm) calculated on humus and carbonate free basis to sum to 100%. Gee & Bauder (1986)
C and N	Total carbon and total nitrogen by dry combustion or Kjeldahl (N)	Not applied on samples that contain calciumcarbonate. Matejovic (1993)
P	Extractable phosphorus, 0.1 M H_2SO_4	Automated analysis used at Danish Institute of Agricultural Sciences.
Ca, Mg, K, Na, Al	Exchangeable cations in 1 M NH_4NO_3	Al assumed to be trivalent. Stuanes *et al.* (1984)
pH	pH in 0.01 M $CaCl_2$ extract	Soil:solution ratio 1:2.5 (mineral samples) and 1:10 (organic samples).
BS_e	Base saturation: (Ca+Mg+K+Na)/ (Al+ Ca+Mg+K+Na)	Base saturation at soil pH.

Nyskov, afdeling 562. Bregentved

Horizon	Depth	BD	clay	silt	fine sand	coar. sand	C	N	P
	cm	g cm^{-3}	%	%	%	%	mg g^{-1}	mg g^{-1}	mg kg^{-1}
O	-2-0						333	16.3	
A1	0-10	0.80	10	12	51	27	71.5	4.8	15
A2	10-20	1.16	12	15	42	31	18.9	1.3	11
E	20-45	1.40	13	13	47	28	4.4	0.4	16
Bt(g)	45-110	1.53	19	14	41	27	1.4	0.2	72
Btg	110-120	1.66	22	18	39	21	1.1	0.2	211
Cg	120-170	1.70	18	18	42	22	4.0	0.1	271

Horizon	Depth	Ca	Mg	K	Na	Al	BS_e	pH
	cm	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	%	0.01 M $CaCl_2$
O	-2-0							4.1
A1	0-10	23.9	5.9	2.8	1.5	44.6	43	3.3
A2	10-20	2.4	1.3	0.8	0.8	54.9	9	3.5
E	20-45	1.8	1.1	0.7	0.5	43.1	9	3.7
Bt(g)	45-110	23.4	14.7	1.8	1.3	15.3	73	4.3
Btg	110-120	96.2	11.6	2.1	2.1	0.4	100	5.7
Cg	120-170	-*	7.5	1.9	3.4	0.2	-	7.6

*13.2 % $CaCO_3$ in Cg.

Nyskov, afdeling 562. Bregentved

FSL forsøg:	1003
Profilbase:	15331
UTM32:	Ø 695323, N 6136460
Klassifikation:	USDA: Oxyaquic Hapludalf, fine-loamy, mixed, nonacid, mesic WRB: Cutanic Luvisol, medium textured
Beskrevet af:	Ingeborg Callesen, 20. april 2000
Kote:	17 m.o.h.
Landskabstype og form:	Bundmoræne, flad
Træart:	Eg, anlagt 1964-65
Udgangsmateriale:	Moræneaflejring
Profildybde:	120 cm
Grundvandsdybde:	100 cm
Dræningsklasse:	Moderat veldrænet
Lokalitetstype:	75

Beskrivelse af horisonter i jorden:

O	-2	-	0	cm
A1	0	-	10	cm
A2	10	-	20	cm
E	20	-	45	cm
Bt(g)	45	-	110	cm
Btg	110	-	120	cm
Cg	120	-	170	cm

O. Fibrist; meget hyppige fine rødder med tilfældig fordeling; blade (nye og delvist nedbrudte) samt vissent græs; horisontgrænse abrupt og jævn

A1. Sort (10 YR 3/1 f) lerholdigt siltet sand; meget humusrig; intet gleypræg; krummestruktur; konsistens svagt klæbende; ikke plastisk i våd tilstand; hyppige rødder af alle størrelser tilfældigt fordelt; poreindhold i profilen ikke beskrevet, men generelt meget få grove porer; horisontgrænse klar og jævn

A2. Mørk gullig brun (10YR 4/4 f) leret siltet sand; humusrig; intet gleypræg; krummestruktur; konsistens svagt klæbende; ikke plastisk i våd tilstand; få mellemgrove rødder med tilfældig fordeling; horisontgrænse klar og jævn

E. Brungul (10 YR 6/6 f) leret siltet sand; humusfattig; strukturløs; konsistens svagt klæbende; ikke plastisk i våd tilstand; få grove rødder med tilfældig fordeling; horisontgrænse klar og bølget

Bt(g). Gullig brun (10YR 5/8 f) ler; humusfattig; 50% bleg gule (2.5Y 7/3) pletter; subangulære mellemstore ustabile aggregater; konsistens svagt klæbende; svagt plastisk i våd tilstand; usammenhængende lerskin i porer; meget få rødder af alle størrelser med tilfældig fordeling; horisontgrænse gradvis og jævn

Btg. Bleg gul (2.5Y 7/4 f) ler; humusfattig; få eller ingen gullig brune (10YR 5/8) pletter på grålig/blålig bund; små afrundede forvitrede sten; struktur kompakt massiv, konsistens svagt klæbende, svagt plastisk i våd tilstand; meget få rødder af varierende størrelse

Cg. Lys gullig brun (2.5Y 6/3 f) ler; humusfattig; sprøde subangulære blokke; smuldrende konsistens; meget få fine rødder; kalkholdig

Christianssæde Afd. 308, Pederstrup-Christianssæde

Horizon	Depth	BD	clay	silt	fine sand	coar. sand	C	N	P
	cm	g cm^{-3}	%	%	%	%	mg g^{-1}	mg g^{-1}	mg kg^{-1}
O	-2-0						385	15.1	
A1	0-5	n.a.	12	10	49	29	28.0	2.1	110
A2	5-25	n.a.	12	11	50	27	15.0	1.7	110
Bt	25-50	n.a.	15	18	44	23	4.0	0.5	240
Btg	50-73	n.a.	18	20	39	24			380
Ckg	73-110	n.a.	9	16	53	22			

Horizon	Depth	Ca	Mg	K	Na	Al	BS_e	pH
	cm	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	%	0.01 M $CaCl_2$
O	-2-0							4.4
A1	0-5	46.0	6.0	1.2	n.a.	n.a.	-	3.8
A2	5-25	93.0	4.0	1.0	n.a.	n.a.	-	5.2
Bt	25-50	122	6.0	1.8	n.a.	n.a.	-	6.2
Btg	50-73	(217)*	5.0	1.2	n.a.	n.a.	-	7.5
Ckg	73-110	-*	3.0	0.7	n.a.	n.a.	-	7.7

* 1% $CaCO_3$ in Btg, 28% $CaCO_3$ in Ckg.

(Raulund-Rasmussen & Vejre, 1995)

Christians-sæde Afd. 308, Pederstrup-Christianssæde

FSL forsøg:	1004
Profilbase:	10161
UTM32:	Ø 651929, N 6072566 (forsøgets SV hjørne)
Klassifikation:	USDA: Oxyaquic Hapludalf, coarse-loamy, mixed, nonacid, mesic WRB: Orthicalcic Luvisol, medium textured
Beskrevet af:	Karsten Raulund-Rasmussen, 1994
Kote:	10 m.o.h.
Landskabsform:	Moræneflade
Træart:	Rødgran, anlagt 1964-65
Udgangsmateriale:	Moræneler
Dræningsklasse:	Moderat veldrænet
Lokalitetstype:	76 (dele af forsøget har lokalitetstype 8 for vand)

Beskrivelse af horisonter i jorden:

Billede mgl.

O	-2 -	0 cm	Organisk materiale
A1	0 -	5 cm	Sandblandet ler, humusrig
A2	5 -	25 cm	Sandblandet ler, humusholdig
Bt	25 -	50 cm	Ler, humusfattig
Btg	50 -	73 cm	Ler
Ckg	73 -	110 cm	Lerblandet sand, stærkt kalkholdig

St. Dyrehave, afd. 57, Frijsenborg

FSL forsøg:	1005
Profilbase:	15221
UTM32:	Ø 556227, N 6233655
Klassifikation:	USDA: Ultic oxyaquic Hapludalf, coarse-loamy, mixed, acid, mesic WRB: Hyperalbic Luvisol, medium textured
Beskrevet af:	Ingeborg Callesen, 24. oktober 1999
Kote:	75 m.o.h.
Landskabstype og form:	Moræneflade, svagt bølget
Træart:	Bøg, 1964-65
Udgangsmateriale:	Moræneaflejringer
Profildybde:	150 cm
Dræningsklasse:	Ufuldstændigt drænet
Lokalitetstype:	74

Bemærkninger: Dobbelt jordbundsudvikling, både lessivering til Bt og podsolering af den øvre del af B har fundet sted. Afblegede sandkorn i AE.

Beskrivelse af horisonter i jorden:

O	-1 -	0 cm
A	0 -	25 cm
AE	25 -	35 cm
Bh /Bhs(g)m	35 -	50 cm
Bs(g)	50 -	60 cm
Bt(g)	60 -	150 cm
C	190 -	200 cm

O. Løs litter og svagt nedbrudte blade, kviste og knopskæl; horisontgrænse abrupt og jævn

A. Meget mørk brun (10 YR 2/2 f) lerholdigt siltet sand; meget humusrig; krummestruktur; fine ustabile aggregater (f); løs konsistens; mange porer af varierende størrelse; hyppige rødder af alle størrelser tilfældigt fordelt; horisontgrænse klar og bølget

AE. Mørkebrun (10 YR 4/3 f) lerholdigt siltet sand; humusrig; krummestruktur; fine ustabile aggregater (f); løs konsistens; mange porer af varierende størrelse; hyppige rødder af alle størrelser tilfældigt fordelt; horisontgrænse klar og irregulær

Bh/Bhs(g)m. Sort (5YR 2.5/1 f) og mørk brun (7.5YR 3/4 f) leret siltet sand; humusrig; 40-50% rødgule (5YR 5/6 f) og lys brungrå (2.5 Y 6/2 f) brogede fine pletter med knivskarp grænse; kompakt massiv, ekstrem fast konsistens; kontinuert stærk cementeret al-lag; sammenhængende moderat tykke humus/ sesquioxid-belægninger på aggregatoverflader; en del medium porer; nogle fine rødder tilfældigt fordelt; belægninger af humus og sesquioxider horisontgrænse abrupt og irregulær

Bs(g). Mørk gullig brun (10 YR 4/6 f) lerholdigt siltet sand; humusholdig; pletter på brunlig eller gullig bund; 0-10% store afrundede uforvitrede sten; struktur kompakt massiv (f); fast konsistens; evt. fragipan; sammenhængende moderat tykke mørkebrune (7.5YR 3/2 f) humus/sesquioxidbelægninger på aggregatoverflader; en del medium porer; få fine og medium rødder som ses i sprækker; horisontgrænse gradvis og jævn

Bt(g). Lys grå (5Y 7/1 f) ler med indblanding af 20-30% lerholdigt siltet sand; humusfattig; kraftigt brune (7.5YR 5/8) pletter på grålig eller blålig bund; 0-10% store afrundede uforvitrede sten; angulær struktur; stabile aggregater (våd); konsistens klæbende; meget få mellemgrove rødder, som findes i sandinklusionen i dybden 150 cm. Lerskin observeret i hele horisontens udstrækning

C. Gullig brun (10 YR 5/4 f) ler; humusfattig; svagt kalkholdig

St. Dyrehave, afd. 57, Frijsenborg

Horizon	Depth	BD	clay	silt	fine sand	coar sand	C	N	P
	cm	g cm^{-3}	%	%	%	%	mg g^{-1}	mg g^{-1}	mg kg^{-1}
O	-1-0						405.1	19.2	
A	0-25	0.92	13	17	52	18	59.2	3.5	186
AE	25-35	1.16	9	14	51	26	19.5	0.9	22
Bh /Bhs(g)m	35-50	1.74	10	14	41	35	28.1	1.2	91
Bs(g)	50-60	1.62	15	16	56	13	6.2	0.3	132
Bt(g)	60-150	1.77	18	13	47	23	1.8	0.1	143

Horizon	Depth	Ca	Mg	K	Na	Al	BS_e	pH
	cm	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	%	0.01 M $CaCl_2$
O	-1-0							4.7
A	0-25	5.0	1.5	1.9	0.8	49.5	16	3.6
AE	25-35	2.2	0.4	0.3	0.7	27.6	12	3.9
Bh /Bhs(g)m	35-50	9.3	1.3	0.5	1.3	40.4	23	4.1
Bs(g)	50-60	7.2	1.3	0.6	1.0	37.6	21	4.1
Bt(g)	60-150	10.0	1.7	1.0	1.1	37.3	27	3.9

Ludvigskov Afd. 33, Holsteinborg

Horizon	Depth	BD	clay	silt	fine sand	coar. sand	C	N	P
	cm	g cm^{-3}	%	%	%	%	mg g^{-1}	mg g^{-1}	mg kg^{-1}
O	-2-0						444.8	14.2	
A	0-20	n.a.	11	11	54	24	9.6	1.0	61
AE	20-55	n.a.	10	10	53	27	5.5	0.7	84
E	55-85	n.a.	11	6	74	9	0.4	0.2	99
Bt	85-120	n.a.	28	21	40	12	1.4	0.4	181
C1	120-170	n.a.	18	15	49	18	0.2	0.0	221

Horizon	Depth	Ca	Mg	K	Na	Al	BS_e	pH
	cm	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	%	0.01 M $CaCl_2$
O	-2-0							4.1
A	0-20	13.4	2.7	0.8	n.a.	n.a.	-	3.7
AE	20-55	52.1	6.9	0.9	n.a.	n.a.	-	4.5
E	55-85	46.7	5.7	1.0	n.a.	n.a.	-	5.4
Bt	85-120	155.3	9.7	1.9	n.a.	n.a.	-	6.1
C1	120-170	98.0	7.1	1.6	n.a.	n.a.	-	6.3

(Vesterdal & Raulund-Rasmussen, 1998)

Ludvigskov Afd. 33, Holsteinborg

FSL forsøg:	1006
Profilbase:	10201
UTM32:	Ø 658182, N 6123847 (forsøgets SV hjørne)
Klassifikation:	USDA : Typic Hapludalf, fine-loamy, mixed, nonacid, mesic WRB : Luvisol, medium textured
Beskrevet af:	Lars Vesterdal 1995
Kote:	25 m.o.h.
Landskabstype og form:	Randmorænelandskab, småbakket
Træart:	Abies grandis og Sitkagran, anlagt 1964-65
Udgangsmateriale:	Moræneler
Dræningsklasse:	Veldrænet
Lokalitetstype:	35

Beskrivelse af horisonter i jorden:

Billede mgl. (evt. 275)	O	-2 - 0 cm
	A	0 - 20 Cm
	AE	20 - 55 cm
	E	55 - 85 cm
	Bt	85 - 120 cm
	C1	120 - 170 cm
	C2	170 - 190 cm

O. Løst lejret litter

A. Meget mørk gråbrun (10YR 3/2 f) sandblandet ler, humusholdig

AE. Mørkebrun (10YR 3/3 f) lerblandet sand, humusfattig

E. Sandblandet ler, humusfattig

Bt. Gullig brun (10YR 5/4 f) svær ler, humusfattig

C1. Ler, humusfattig

C2. Ler, svagt kalkholdig

Lovrup skov, Afd 185, Lindet distrikt

FSL forsøg	1007
Profilbase:	10021
UTM32:	Ø 492780, N 6110720 (forsøgets SV-hjørne)
Klassifikation:	USDA: Typic Quarzipsamment, sandy, acid, mesic, non-cemented WRB: Haplic Umbrisol, coarse textured
Beskrevet af:	Karsten Raulund-Rasmussen. August, 1988.
Kote:	36 m.o.h.
Landskabsform og type:	Toftlund bakkeø, jævn flade
Træart:	Rødgran, plantet 1964
Udgangsmateriale:	Flyvesand, morænesand (Saale) og smeltevandssand
Dræningsklasse:	Veldrænet
Lokalitetstype:	32

Beskrivelse af horisonter i jorden:

O	-7 -	0 cm
A	0 -	6 cm
E	6 -	18 cm
Bh	15 -	22 cm
Bsh	22 -	60 cm
BC	60 -	80 cm
C	80 -	95 cm
2C	95 -	cm

O. Meget mørkebrun (10YR 2/2 f) organisk materiale, en del fine medium og grove rødder, nogen faunaaktivitet (biller og myrer), abrupt jævn grænse

A. Sort (10YR 2/1 f) meget humusrig, sand, enkeltkornstruktur, løs konsistens (f), hyppige meget fine, fine, medium og grove rødder, klar bølget grænse.

E. Gullig brun (10YR 5/4 f) humusholdig, sand, enkeltkornstruktur, en del meget fine, fine, medium og grove rødder, klar bølget grænse.

Bh. Mørk rødbrun (5YR 3/3 f) humusholdig, lerblandet sand, enkeltkornstruktur, sprød konsistens (f), tydelige belægninger af jernoxider og humus på sandkorn, meget få små afrundede forvitrede og uforvitrede sten (granit og kvarts), få meget fine medium og grove rødder, klar bølget grænse.

Bsh. Gullig brun (10YR 5/6 f) humusholdig, lerblandet sand, meget sprød konsistens (f), mange tydelige tynde belægninger af jernoxider og humus på sandkorn, meget få små afrundede forvitrede og uforvitrede sten (granit og kvarts), få meget fine, fine, medium og grove rødder, klar bølget grænse.

BC. Mørkebrun (10YR 4/6 f) humusfattig, sand, svagt cementeret, få kontinuerte oftest lodrette sprækker, få meget fine rødder, meget få afrundede forvitrede små og mellemstore sten, klar jævn grænse.

C. Gul (10YR 7/8 f) humusfattig, sand, enkeltkornstruktur, sprød konsistens (f), få afrundede svagt forvitrede små sten, abrupt jævn grænse.

2C. Gullig rød (5YR 4/6 f) humusfattig, sand, enkeltkornstruktur, svagt cementeret, meget få små afrundede svagt forvitrede sten

Lovrup skov, Afd 185, Lindet distrikt

Hori-zon	Depth cm	BD g cm^{-3}	clay %	silt %	fine sand %	coar. sand %	C mg g^{-1}	N mg g^{-1}	P mg kg^{-1}
O	-7-0						343.0	15.5	55
A	0-6		3	6	45	47	49.7	2.7	10
E	6-15		4	6	46	44	7.9	0.3	6
Bh	15-22		9	7	40	43	12.4	0.6	9
Bsh	22-60		7	7	47	40	9.6	0.5	37
BC	60-80		5	3	49	44	1.4		38
C	80-95		1	1	54	44	0.4		25
2C	95-		3	1	13	83	0.4		36

Hori-zon	Depth cm	Ca $\mu mol_c\, g^{-1}$	Mg $\mu mol_c\, g^{-1}$	K $\mu mol_c\, g^{-1}$	Na $\mu mol_c\, g^{-1}$	Al $\mu mol_c\, g^{-1}$	BS_e %	pH 0.01 M $CaCl_2$
O	-7-0	44.3	34.4	13.2	9.7	20.5	83	3.1
A	0-6	2.6	3.7	1.5	1.8	39.0	20	2.9
E	6-15	0.2	0.2	0.1	0.4	15.2	6	3.9
Bh	15-22	0.4	0.4	0.3	0.4	32.5	4	3.7
Bsh	22-60	0.3	0.2	0.3	0.4	18.1	6	4.2
BC	60-80	0.1	0.1	0.2	0.3	9.1	6	4.4
C	80-95	0.1	0.0	0.2	0.2	6.2	8	4.5
2C	95-	0.1	0.1	0.3	0.5	8.9	11	4.4

(Raulund-Rasmussen, 1993)

Karhus skov, Løvenholm distrikt

Hori-zon	Depth	BD	clay	silt	fine sand	coar. sand	C	N	P
	cm	g cm^{-3}	%	%	%	%	mg g^{-1}	mg g^{-1}	mg kg^{-1}
O	-3-0						359.5	13.8	
A	0-27	n.a.	4	12	37	48	9.4	0.7	119
Bw	27-55	n.a.	3	7	49	42	4.0	0.3	161
BC	55-70	n.a.	4	9	49	38	0.8	0.2	223
Cg	70-	n.a.	4	11	44	42	0.6		123

Hori-zon	Depth	Ca	Mg	K	Na	Al	BS_e	pH
	cm	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	%	0.01 M $CaCl_2$
O	-3-0							4.9
A	0-27	4.7	0.6	0.6	n.a.	n.a.	-	4.1
Bw	27-55	4.8	0.5	0.4	n.a.	n.a.	-	4.8
BC	55-70	2.1	0.3	0.4	n.a.	n.a.	-	4.7
Cg	70-	7.8	0.7	0.7	n.a.	n.a.	-	4.5

(Vesterdal & Raulund-Rasmussen, 1998)

Karhus skov, Løvenholm distrikt

FSL forsøg:	1008
Profilbase:	10211
UTM32:	Ø 594399, N 6258113
Klassifikation:	USDA: Oxyaquic Quarzipsamment, sandy, mixed, acid, mesic WRB: Hyperdystric Arenosol, medium textured
Beskrevet af:	Lars Vesterdal, 1995
Kote:	34 m.o.h.
Landskabstype og form:	Dødislandskab, småbakket
Træart:	Rødgran, anlagt 1964-65
Udgangsmateriale:	Morænesand overlejret af puder af fint flyvesand
Dræningsklasse:	Moderat veldrænet
Lokalitetstype:	73

Beskrivelse af horisonter i jorden (inddeling: 10 cm):

O	-3 - 0 cm
A	0 - 27 cm
Bw	27 - 55 cm
BC	55 - 70 cm
Cg	70 - cm

O. Organisk materiale

A. Mørkebrun (10YR 3/3 f) sand, humusholdig; kompakt massiv, let smuldrende; nogle rødder af blandet størrelse, få medium porer, meget få små kantede krystallinske uforvitrede sten, horisontgrænse abrupt og bølget.

Bw. Mørk gulbrun (10 YR 4/4 f) sand, humusfattig, kompakt massiv, let smuldrende; få fine og medium store rødder, få medium store porer, meget få små kantede krystallinske uforvitrede sten, horisontgrænse klar og bølget.

BC. Brun (10YR 5/3 f), sand, humusfattig, kompakt massiv, fast, meget få fine rødder, få medium store porer, få (0-10%) kantede krystallinske forvitrede sten af blandet størrelse, horisontgrænse klar og jævn.

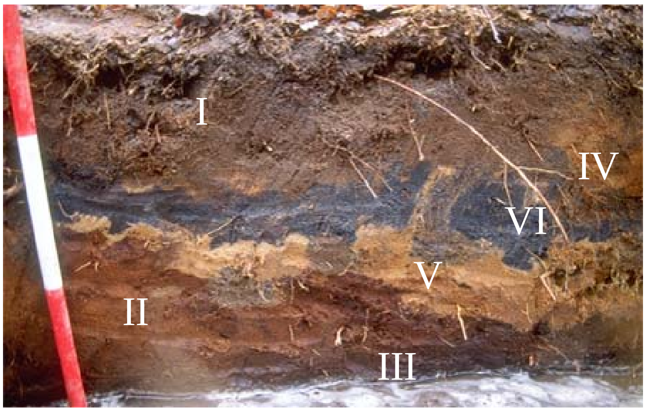
Cg. Lys brungrå (10YR 6/2 f), 30-40% gulbrune (10YR 5/4 f) afrundede store diffuse pletter, sand, humusfattig, kompakt massiv, fast, få fine rødder, få medium store porer, 20-30% kantede krystallinske meget forvitrede sten af blandet størrelse.

Hastrup plantage, afd. 265, Palsgård

FSL forsøg:	1009
Profilbase:	15231
UTM32:	Ø 513052, N 6199278
Klassifikation:	USDA: Aquod eller Humod, sandy, acid
	WRB: Anthric Podsol, coarse textured
Beskrevet af:	Ingeborg Callesen, 6. december 1999
Kote:	59 m.o.h.
Landskabstype og form:	Smeltevandsslette, flad
Træart:	Bøg, 1964-65
Udgangsmateriale:	Flyvesand og senglacialt smeltevandssand
Dræningsklasse:	Dårligt drænet
Lokalitetstype:	32

Bemærkninger: Profilen er dybdepløjet. Billedet viser en profilvæg parallelt med pløjeretningen. Skårene kunne erkendes på en profilvæg vinkelret på denne. Under vandspejlet i 60 cm starter en humusrig Bhs, som pløjningen ikke har brudt op.

Beskrivelse af horisonter i jorden:



App I	0 - 20 cm
‘Ap/Bh VI	20 - 30 cm
Bhs IV	26 - 40 cm
Bs II	30 - 60 cm
Bh III	30 - 60 cm
Bs V	30 - 40 cm

App I. Mørkebrunt (7.5 YR 3/2 f) svagt lerholdigt mellemsand; humusrig; strukturløs (f); løs konsistens; meget hyppige rødder af alle størrelser; forstyrret af dybdebearbejdning

'Ap/Bh VI. Sort (10 YR 2/1 f) svagt lerholdigt mellemsand; humusrig; strukturløs (f); let smuldrende konsistens; meget hyppige rødder af alle størrelser; forstyrret af dybdebearbejdning

Bhs IV. Mørk brun (7.5 YR 3/4 f) mellemsand; humusholdig; strukturløs (f); løs konsistens; meget hyppige rødder af alle størrelser; dybdebearbejdet

Bs II. Mørk brun (5YR 2.5/2 f) mellemsand; humusholdig; strukturløs (f); løs konsistens; meget hyppige rødder af alle størrelser; dybdebearbejdet

Bh III. Sort (7.5YR 2.5/1 f) svagt lerholdigt mellemsand; humusholdig; strukturløs (f); let smuldrende konsistens; diskontinuert svag cementering (spodisk materiale, knust ved dybdebearbejdning); meget hyppige rødder af alle størrelser

Bs V. Kraftigt brun (7.5YR 4/6 f) mellemsand; humusfattig; strukturløs (f) løs konsistens

Hastrup plantage, afd. 265, Palsgård

Hori-zon	Depth cm	BD $g\ cm^{-3}$	clay %	silt %	fine sand %	coar. sand %	C $mg\ g^{-1}$	N $mg\ g^{-1}$	P $mg\ kg^{-1}$
O							305.0	16.4	
App I	0-20	1.20	3	2	28	67	17.0	1.0	6
’Ap/Bh VI	20-30	1.38	3	2	29	66	36.1	1.5	3
Bhs IV	26-40	1.37	2	2	19	77	10.2	0.3	6
Bs II	30-60	1.48	2	2	39	57	9.0	0.3	2
Bh III	30-60	1.44	3	1	20	76	14.0	0.5	2
Bs V	30-40	1.51	2	1	18	79	4.1	0.2	9

Hori-zon	Depth cm	Ca $\mu mol_c\ g^{-1}$	Mg $\mu mol_c\ g^{-1}$	K $\mu mol_c\ g^{-1}$	Na $\mu mol_c\ g^{-1}$	Al $\mu mol_c\ g^{-1}$	BS_e %	pH 0.01 M $CaCl_2$
O								4.3
App I	0-20	3.0	0.8	0.5	1.1	20.2	21	3.4
’Ap/Bh VI	20-30	21.9	2.6	0.4	0.9	20.4	56	3.7
Bhs IV	26-40	3.8	0.4	0.1	0.4	16.7	22	4.0
Bs II	30-60	2.4	0.3	0.2	0.4	16.6	17	3.9
Bh III	30-60	7.5	0.8	0.1	0.7	17.8	34	3.8
Bs V	30-40	3.0	0.4	0.1	0.5	11.3	26	4.0

Højbjerg skov, afd. 292, Skjoldenæsholm

Horizon	Depth	BD	clay	silt	fine sand	coar. sand	C	N	P
	cm	g cm^{-3}	%	%	%	%	mg g^{-1}	mg g^{-1}	mg kg^{-1}
Oi	-1-0						230.8	8.8	
A	0-18	1.07	12	18	38	33	15.7	1.5	206
AE	18-30	1.20	11	15	37	37	5.3	0.5	299
E(g)	30-53	1.69	10	13	38	38	2.2	0.1	196
Bt(g)	53-100	1.53	18	12	37	34	0.9	0.2	255
BC(g)	100-160	1.60	12	13	40	35	2.1	0.1	319

Horizon	Depth	Ca	Mg	K	Na	Al	BS_e	pH
	cm	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	%	0.01 M $CaCl_2$
Oi	-1-0							5.2
A	0-18	36.2	3.3	1.7	0.7	10.4	80	4.2
AE	18-30	38.0	1.7	0.7	1.0	1.9	96	5.1
E(g)	30-53	40.4	2.3	1.0	1.0	1.2	97	5.3
Bt(g)	53-100	48.9	7.1	1.9	1.3	1.2	98	5.3
BC(g)	100-160	*-	3.6	1.7	1.4	0.2	100	7.7

*8.3 % $CaCO_3$ i BC(g)

Højbjerg skov, afd. 292, Skjoldenæsholm

FSL forsøg:	1010
Profilbase:	15321
UTM32:	Ø 678435, N 6158831
Klassifikation:	USDA: Oxyaquic Hapludalf, coarse-loamy, mixed, nonacid, mesic WRB: Cutanic Luvisol
Beskrevet af:	Ingeborg Callesen, 18. april 2000
Kote:	80 m.o.h.
Landskabstype og form:	Dødislandskab, kuperet
Træart:	Bøg, 1964-65
Udgangsmateriale:	Moræneaflejringer
Dræningsklasse:	Moderat veldrænet
Lokalitetstype:	85

Beskrivelse af horisonter i jorden (inddeling 20 cm):

Oi	-1 -	0 cm
A	0 -	18 cm
AE	18 -	30 cm
E(g)	30 -	53 cm
Bt(g)	53 -	100 cm
BC(g)	100 -	160 cm

Oi. Bøgelitter, knopskæl og kviste

A. Mørk gråbrun (10YR 4/2 f) leret siltet sand; humusholdig; krummestruktur; fine, ustabile aggregater (våd), konsistens svagt klæbende; mange porer af varierende størrelse; meget hyppige rødder af alle størrelser med tilfældig fordeling; horisontgrænse klar og jævn

AE. Gullig brun (10 YR 5/4 f) leret siltet sand; humusfattig; diffuse jernudfældningspletter; 0-10% sten af variende type og forvitringstilstand; sprøde angulære blokke; fine ustabile aggregater (w); spredte tynde belægninger af ler og silt; mange porer af varierende størrelse; meget hyppige rødder af alle størrelser med tilfældig fordeling; horisontgrænse klar og jævn

E(g). Meget bleg brun (10YR 7/4 f) leret siltet sand med indblanding af 0-10% grovsand; humusfattig; gleypræg: våde, afblegede farver; 10-20% sten af varierende type og forvitringstilstand (mange stærkt forvitrede); angulær struktur, mellemstore, ustabile aggregater (w), konsistens klæbende, ikke plastisk i våd tilstand; mange porer af varierende størrelse; få rødder af alle størrelser med tilfældig fordeling; horisontgrænse klar og jævn

Bt(g). Meget bleg brun (10YR 8/4 f) ler; humusfattig; mellemstore klart afgrænsede redoxpletter; 10-20% sten af varierende type og tilstand, mange stærkt forvitrede; angulære mellemstore ustabile aggregater (våd); konsistens klæbende, ikke plastisk i våd tilstand; sammenhængende tykke belægninger af lermineraler; en del porer af varierende størrelse; meget få fine og mellemgrove rødder med tilfældig fordeling; tydelige lercutans i porer; mindst 10% helt opløste sten, hvor mineralfarven stadig erkendes i matrix

BC(g). Gullig brun (10 YR 5/4 f) og lys oliven brun (2.5Y 5/3 f) leret siltet sand; humusfattig; svagt kalkholdig; 10-20% meget store blandede sten af blandet form og tilstand; let smuldrende konsistens (f); ingen cementering; farveindblandingen har karakter af svag mottling

Stenholts Vang, afd. 555, Frederiksborg distrikt

FSL forsøg	1011
Profilbase:	10031
UTM32:	Ø 709418, N 6206350
Klassifikation:	USDA: Typic Hapludalf, fine-loamy, mixed, non-acid, mesic WRB: Cutanic Luvisol, medium textured
Beskrevet af:	Karsten Raulund-Rasmussen, August 1988
Kote:	35 m.o.h.
Landskabsform:	Dødislandskab, småkuperet
Træart:	Bøg, plantet 1965
Udgangsmateriale:	Moræneler fra Weichsel/ ferskvandssedimenter
Dræningsklasse:	Moderat veldrænet
Lokalitetstype:	76

Beskrivelse af horisonter i jorden:

Oi	-3 -	0 cm	
A	0 -	30 cm	
AB	30 -	50 cm	
Btg1	50 -	85 cm	
Btg2	85 -	120 cm	
BCg	120 -	cm	

Oi. Løst lejret bøgelitter

A. Mørkebrun (10YR 3/3 f) humusholdig ler, mellemgrov krummestruktur, ustabile aggregater, mange fine kontinuerte tilfældigt fordelte porer, hyppige rødder af alle størrelser, klar og jævn overgang.

AB. Mørk gulligbrun (10YR 4/6 f) humusfattig ler, svag fin krummestruktur, sprød konsistens (f), få fine kontinuerte tilfældigt fordelte porer, få meget fine og fine rødder, gradvis jævn overgang.

Btg1. Gullig brun (10YR 5/6 f), få tydelige, diffust afgrænsede rødgule (5YR 5/6 f) og gullig brune (10YR 5/4) pletter, humusfattig, ler, mellemstore subangulære blokke, fast konsistens (f), lerskin på aggregatoverflader, få fine kontinuerte tilfældigt fordelte porer, diffus jævn overgang.

Btg2. Gullig brun (10YR 5/4 f) humusfattig, hyppige mellemstore og store klart afgrænsede mørkebrune (7.5YR 4/4) pletter og lodrette slirer, ler; grove meget stabile angulære blokke, fast konsistens (f), tynde lerskin på aggregatoverflader, få fine kontinuerte tilfældigt fordelte porer, få meget fine og fine rødder, diffus jævn overgang.

BCg. Gullig brun (10YR 5/4 f); hyppige mellemstore og store klart afgrænsede lyse gullig brune (7.5YR 4/4 f) pletter, humusfattig, svær ler; grove meget stabile angulære blokke, tynde lerskin på aggregatoverflader, få fine kontinuerte tilfældigt fordelte porer, meget få små bløde sfæriske sorte mangankonkretioner.

Stenholts Vang, afd. 555, Frederiksborg distrikt

Horizon	Depth	BD	clay	silt	fine sand	coar. sand	C	N	P
	cm	g cm^{-3}	%	%	%	%	mg g^{-1}	mg g^{-1}	mg kg^{-1}
Oi	-3-0						378.2	13.0	
A	0-30	n.a.	16	24	50	10	7.7	0.9	126
AB	30-50	n.a.	23	22	52	4	1.6	0.3	112
Btg1	50-85	n.a.	24	29	44	3	0.6	0.2	182
Btg2	85-120	n.a.	22	28	48	3	0.2		230
BCg	120-	n.a.	25	25	46	3	0.2		263

Horizon	Depth	Ca	Mg	K	Na	Al	BS_e	pH
	cm	$\mu mol_c\ g^{-1}$	$\mu mol_c\ g^{-1}$	$\mu mol_c\ g^{-1}$	$\mu mol_c\ g^{-1}$	$\mu mol_c\ g^{-1}$	%	0.01 M $CaCl_2$
Oi	-3-0							5.1
A	0-30	28.4	3.0	1.5	0.6	1.8	95	4.9
AB	30-50	42.3	5.1	1.8	0.8	1.2	98	5.3
Btg1	50-85	40.2	7.2	1.8	0.8	1.2	98	5.4
Btg2	85-120	40.4	20.1	1.9	0.9	1.2	98	5.5
BCg	120-	37.2	28.7	2.0	1.2	2.8	96	5.1

(Raulund-Rasmussen, 1993)

Skodsbøl skov, Afd. 301, Gråsten

Horizon	Depth cm	BD $g\ cm^{-3}$	clay %	silt %	fine sand %	coar. sand %	C $mg\ g^{-1}$	N $mg\ g^{-1}$	P $mg\ kg^{-1}$
Oi	-1-0						413.4	16.0	
A	0-27	0.99	32	33	27	8	31.3	2.9	41
B(g)1	27-68	1.40	38	37	18	7	3.7	0.4	67
B(g)2	68-105	1.58	45	35	16	3	2.2	0.3	346
Cg	105-160	1.34	34	42	24	0	6.1	0.2	313

Horizon	Depth cm	Ca $\mu mol_c\ g^{-1}$	Mg $\mu mol_c\ g^{-1}$	K $\mu mol_c\ g^{-1}$	Na $\mu mol_c\ g^{-1}$	Al $\mu mol_c\ g^{-1}$	BS_e %	pH 0.01 M $CaCl_2$
Oi	-1-0							5.2
A	0-27	177.7	22.7	5.3	2.9	1.9	99	4.9
B(g)1	27-68	192.5	23.5	4.4	3.2	0.3	100	5.8
B(g)2	68-105	246.5	22.6	5.5	5.4	0.2	100	6.5
Cg	105-160	-*	12.8	4.3	5.9	0.2	100	7.5

*16.3% $CaCO_3$ in Cg.

Skodsbøl skov, Afd. 301, Gråsten

FSL forsøg:	1012
Profilbase:	15241
UTM32:	Ø 540792, N 6085536
Klassifikation:	USDA: Typic Endoaquoll, fine, nonacid, mesic WRB: Endostagnic Phaeozem, fine textured
Beskrevet af:	Ingeborg Callesen, 5. december 1999
Kote:	7 m.o.h.
Landskabstype, form:	Randmorænelandskab
Træart:	Bøg, anlagt 1964-65
Udgangsmateriale:	Issøaflejring
Dræningsklasse:	Ufuldstændigt drænet
Lokalitetstype:	86

Bemærkninger; Op til 1 cm brede og over 15 cm dybe sprækker i A i sensommeren 2000 som følge af udtørring.

Beskrivelse af horisonter i jorden:

Oi	-1 - 0 cm
A	0 - 27 cm
B(g)1	27 - 68 cm
B(g)2	68 - 105 cm
Cg	105 - 160 cm

Oi. Løs bøgelitter, horisontgrænse abrupt og jævn

A. Meget mørk gråbrun (10 YR 3/2 f) siltet svær ler; humusrig; krummestruktur (v); meget klæbende meget plastisk i våd tilstand; mange porer af varierende størrelse; utallige rødder af alle størrelser tilfældigt fordelt; overfladebearbejdet ved anlæg; horisontgrænse klar og jævn

B(g)1. Brun (10YR 5/3 f) og grønlig grå (5GY 5/1 f) siltet svær ler; humusfattig; gleypletter på brunlig bund; indeholder ikke kalk; små bløde afrundede noduler af Fe- og Mn-oxider/hydroxider; subangulær struktur (w); meget klæbende meget plastisk i våd tilstand; mange fine porer; meget få mellemgrove rødder tilfældt fordelt; horisontgrænse gradvis og jævn

B(g)2. Grønlig grå (5GY 5/1 f) siltet svær ler; humusfattig; pletter på grålig eller blålig bund; indeholder ikke kalk; små bløde afrundede noduler af Fe- og Mn-oxider/hydroxider; subangulær struktur (v); meget klæbende, meget plastisk i våd tilstand; ingen cementering; meget få mellemgrove rødder, som ses både i ormegange og sprækker; horisontgrænse klar og jævn

Cg. Grønlig grå (5GY 6/1 w og 5G 6/1 w) siltet svær ler; issøaflejringer; humusfattig; gullig brune (10YR 5/6 f) pletter på grålig eller blålig bund; kalkholdig; 20-30% brogede fine redoxpletter med knivskarp grænse; små bløde afrundede noduler af Fe- og Mn-oxider/hydroxider; subangulær struktur (w); meget klæbende, meget plastisk i våd tilstand; usammenhængende moderat tykke belægninger af calciumcarbonat på aggregatoverflader; nogle mellemgrove rødder, som ses både i ormegange og sprækker. Overraskende mange rødder i Cg.

Rødhus plantage, afd. 90: 92, Hanherred distrikt

FSL forsøg	1013
Profilbase:	15251
UTM32:	Ø 533226, N 6339015 (forsøgets SV hjørne)
Klassifikation:	USDA: Typic Psammaquent, sandy, acid WRB: Arenic Gleysol, coarse textured
Beskrevet af:	Ingeborg Callesen og Karsten Raulund-Rasmussen, 22. oktober 1999
Kote:	15 m.o.h.
Landskabsform:	Klitter
Træart:	Stilk-Eg, anlagt 1964 - 1965
Udgangsmateriale:	Flyvesand
Dræningsklasse:	Dårligt drænet
Lokalitetstype:	81

Beskrivelse af horisonter i jorden (inddeling 20 cm):

Oe	-10 -	-5 cm
Oa	-5 -	0 cm
A	0 -	2 cm
E	2 -	5 cm
Bs	5 -	35 cm
Cg	35 -	88 cm

Oe. Mørk rødbrun (5YR 3/3 f) organisk lag; meget hyppige rødder af alle størrelser med tilfældig fordeling; horisontgrænse abrupt og jævn

Oa. Meget mørk brun (10YR 2/2 f) organisk lag; meget hyppige rødder af alle størrelser med tilfældig fordeling; horisontgrænse abrupt og jævn

A. Meget mørk gråbrun (10 YR 3/2 f) finsand; flyvesandsaflejringer; humusrig; intet gleypræg; strukturløs (f); løs konsistens; meget hyppige rødder af alle størrelser med tilfældig fordeling; horisontgrænse abrupt og jævn

E. Gullig brun (10 YR 5/4 f) finsand; humusfattig; intet gleypræg; indeholder ikke kalk; strukturløs (f); løs konsistens; nogle rødder af alle størrelser med tilfældig fordeling; humusrig rodgang til dybden 30 cm; horisontgrænse klar og jævn

Bs. Brungul (10 YR 6/6 f) finsand; humusfattig; diffuse jernudfældningspletter; 0-10% lodret stribede store redoxpletter som er knivskarpt afgrænset; strukturløs (f); løs konsistens; usammenhængende tynde belægninger af sesquioxider på sandkorn; få rødder af alle størrelser med tilfældig fordeling; horisontgrænse diffus og jævn

Cg. Grønlig grå (5GY 6/1 f) finsand; humusfattig; få eller ingen pletter på grålig/blålig bund; strukturløs (v); løs konsistens; usammenhængende tynde belægninger af sesquioxider på sandkorn; få rødder med tilfældig fordeling; belægninger af typen grøn rust.

Rødhus plantage, afd. 90: 92, Hanherred distrikt

Hori-zon	Depth	BD	clay	silt	fine sand	coar. sand	C	N	P
	cm	g cm^{-3}	%	%	%	%	mg g^{-1}	mg g^{-1}	mg kg^{-1}
Oe	-10--5						416.7	19.7	
Oa	-5-0						228.6	10.8	
A	0-2	1.42	3	2	53	42	20.9	1.4	4
E	2-5	1.42	2	1	44	53	4.6	0.3	4
Bs	5-35	1.57	2	1	58	39	0.9		24
Cg	35-88	1.53	2	1	54	44	0.2		38

Hori-zon	Depth	Ca	Mg	K	Na	Al	BS$_e$	pH
	cm	µmol$_c$ g^{-1}	µmol$_c$ g^{-1}	µmol$_c$ g^{-1}	µmol$_c$ g^{-1}	µmol$_c$ g^{-1}	%	0.01 M $CaCl_2$
Oe	-10--5							3.2
Oa	-5-0							3.1
A	0-2	1.1	0.4	0.3	1.1	10.2	23	3.2
E	2-5	0.2	0.1	0.1	0.4	4.2	17	3.4
Bs	5-35	0.2	0.1	0.1	0.4	3.9	16	3.9
Cg	35-88	0.3	0.1	0.7	0.9	4.1	33	4.1

Katborg Plantage, Ulborg distrikt (Afd. 9), 1014

Horizon	Depth	BD	clay	silt	fine sand	coar. sand	C	N	P
	cm	g cm^{-3}	%	%	%	%	mg g^{-1}	mg g^{-1}	mg kg^{-1}
Olfh	-8-0						409.2	14.9	58
A	0-18	n.a.	2	3	28	67	107.4	3.3	22
E	18-30	n.a.	1	2	9	89	3.6	0.1	6
Bh	30-34	n.a.	11	4	17	68	69.8	2.4	24
Bhs	34-40	n.a.	6	4	16	74	36.2	1.3	20
Bs	40-60	n.a.	3	3	28	66	1.2	0.1	16
BC	60-100	n.a.	1	2	32	65	0.3		10
C	100-130	n.a.	1	3	24	73	0.1		11

Horizon	Depth	Ca	Mg	K	Na	Al	BS_e	pH
	cm	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	%	0.01 M $CaCl_2$
Olfh	-8-0	52.2	44.4	7.6	7.6	22.3	83	3.2
A	0-18	3.9	6.7	2.3	11.8	27.5	47	2.7
E	18-30	0.3	0.1	0.0	0.2	2.3	20	3.4
Bh	30-34	2.0	1.3	0.9	1.3	74.7	7	3.5
Bhs	34-40	0.6	0.4	0.4	0.7	30.9	7	4.1
Bs	40-60	0.2	0.03	0.1	0.4	6.1	10	4.4
BC	60-100	0.1	0.02	0.0	0.2	3.9	7	4.5
C	100-130	0.1	0.01	0.0	0.1	2.8	7	4.6

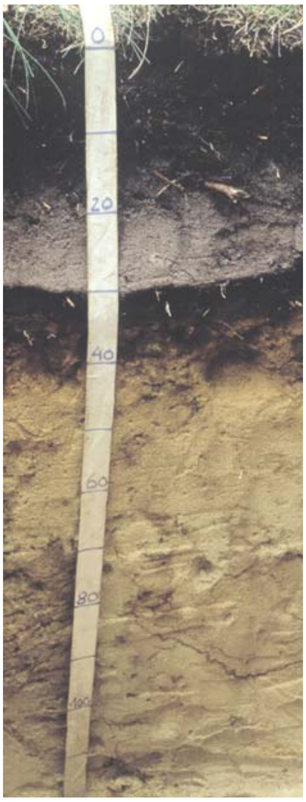
(Raulund-Rasmussen, 1993)

Katborg Plantage, Ulborg distrikt (Afd. 9), 1014

FSL forsøg: 1014
Profilbase: 10001
UTM32: Ø 464619, N 6238810 (ikke præcis).

Klassifikation: USDA: Typic Haplorthod, sandy, mixed/siliceous, acid, mesic, non-cemented
WRB: Haplic Podzol
Beskrevet af: Karsten Raulund-Rasmussen, August, 1988.
Kote: 42 m.o.h.
Landskabsform: Svagt bølget klittopografi
Træart: Skovfyr, plantet 1958
Udgangsmateriale: Morænesand fra Saale istiden
Dræningsklasse: Meget/ ekstremt veldrænet
Lokalitetstype: 32
Bemærkninger: Gravet i nabobevoksningen, der ikke som forsøget er reolpløjet.

Beskrivelse af horisonter i jorden:



Olfh	-8 - 0 cm
A	0 - 18 cm
E	18 - 30 cm
Bh	30 - 34 cm
Bhs	34 - 40 cm
Bs	40 - 60 cm
BC	60 - 100 cm
C	100 - 130 cm

Olfh. Mørk rødbrun (5YR 2.5/2 f) delvist nedbrudt organisk materiale, meget hyppige meget fine, fine, medium og grove rødder, horisontgrænse abrupt og jævn

A. Sort (10YR 2/1 f) meget humusrig; sand, afblegede sandkorn, enkeltkornstruktur, løs konsistens (f), meget få små afrundede forvitrede sten, få meget fine og fine, og meget få medium og grove rødder, klar jævn overgang

E. Gråbrun (10YR 5 / 2 f) humusfattig; sand, enkeltkornstruktur, løs konsistens (f), hyppige små afrundede sten ved overgangen til Bh, horisontgrænse abrupt og jævn

Bh. Sort (10YR 2/1 f) meget humusrig, sandblandet ler, massiv struktur, fast konsistens (f), brudte tynde belægninger af organisk stof på sandkorn, få små forvitrede sten, hyppige meget fine og fine rødder, klar jævn overgang

Bhs. Mørk rødbrun (2.5YR 2.5/2 f) humusrig, lerblandet sand, massiv til medium pladestruktur, sprød konsistens, kontinuerte tynde belægninger af jernoxider på sandkorn, meget få små afrundede sten, meget få meget fine rødder, horisontgrænse gradvis og jævn

Bs. Gullig brun (10YR 5/6 f) få fine tydelige skarpt afgrænsede sorte (10YR 2/1 f) og mørkerøde (2.5YR 2.5/2 f) og få fine klart afgrænsede brune (10 YR 5/3 f) pletter, humusfattig, sand, enkeltkornstruktur, løs konsistens (f), belægninger af jernoxid på sandkorn, meget få, meget fine rødder, meget få små afrundede forvitrede sten, klar jævn grænse

BC. Gullig brun (10YR 5/6 f) få mellemstore tydelige, diffust afgrænsede brungule (10YR 6/6 f) pletter og få tynde fremtrædende skarpt afgrænsede mørke brune (10YR 3/3 f) bånd, humusfattig, sand, enkeltkornstruktur; sprød konsistens (f), ingen rødder, ingen sten, horisontgrænse diffus og jævn

C. Gul (10YR 8/6 f) humusfattig, sand, enkeltkornstruktur, løs konsistens (f).

Tisted Nørskov Afd. 140 a, Nørlund

FSL forsøg:	1015
Profilbase:	10221
UTM32:	Ø 561968, N 6294317
Klassifikation:	USDA: Typic Quarzipsamment, sandy, acid, mesic WRB: Arenic Umbrisol, coarse textured
Beskrevet af:	Karsten Raulund-Rasmussen, august 1988
Kote:	44 m.o.h.
Landskabstype og form:	Dødislandskab, småbakket
Træart:	Rødgran, etableret 1964-65
Udgangsmateriale:	Morænesand
Dræningsklasse:	Meget veldrænet
Lokalitetstype:	33

Bemærkninger: Teksturskift fra Bw til C tyder på to forskellige aflejringer.

Beskrivelse af horisonter i jorden:

O	-2 - 0 cm	Morlag
Ap1	0 - 5 cm	Sort (10YR 2/1 f) lerblandet sand, humusrig
Ap2	5 - 21 cm	Meget mørkt gråt (10YR 3/1 f) sand, humusholdig
Bw1	21 - 51 cm	Brunt (7.5YR 5/3 f) sand, humusholdig
Bw2	51 - 88 cm	Lys gullig brun (2.5Y 6/3 f) lerblandet sand, humusfattig
2C	88 - cm	Oliven gul (2.5Y 6/6 f) sand, humusfattig

Tisted Nørskov Afd. 140 a, Nørlund

Horizon	Depth	BD	clay	silt	fine sand	coar. sand	C	N	P
	cm	g cm^{-3}	%	%	%	%	mg g^{-1}	mg g^{-1}	mg kg^{-1}
O	-2-0						377.3	12.8	
Ap1	0-5	n.a.	5	9	54	32	37.7	2.0	110
Ap2	5-21	n.a.	3	9	58	31	16.8	1.0	76
Bw1	21-51	n.a.	4	13	46	37	5.9	0.5	66
Bw2	51-88	n.a.	5	12	41	41	1.0	0.1	31
2C	88-	n.a.	1	1	48	51	0.9	0.0	35

Horizon	Depth	Ca	Mg	K	Na	Al	BS_e	pH
	cm	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	%	0.01 M $CaCl_2$
O	-2-0							4.4
Ap1	0-5	16.7	2.4	1.2	n.a.	n.a.	-	3.5
Ap2	5-21	8.2	0.7	0.3	n.a.	n.a.	-	4.1
Bw1	21-51	2.3	0.2	0.3	n.a.	n.a.	-	4.3
Bw2	51-88	3.8	0.3	0.6	n.a.	n.a.	-	4.2
2C	88-	0.8	0.1	0.4	n.a.	n.a.	-	4.4

(Vesterdal & Raulund-Rasmussen, 1998)

Ring skov, afd. 327, Matrup distrikt

Hori-zon	Depth	BD	clay	silt	fine sand	coar. sand	C	N	P
	cm	g cm^{-3}	%	%	%	%	mg g^{-1}	mg g^{-1}	mg kg^{-1}
A	0-24	n.a.	14	14	39	33	17.6	1.5	117
EA	24-34	n.a.	12	11	44	34	6.0	0.5	84
2Bt	34-53	n.a.	22	15	37	26	3.2	0.3	21
2EB	53-76	n.a.	16	9	42	34	1.7	0.2	30
2Bt	76-93	n.a.	21	11	39	29	1.5	0.2	36
3BC	93-115	n.a.	10	5	42	43	0.6	0.1	48
3BC	115-150	n.a.	18	11	43	29	0.7	0.1	75

Hori-zon	Depth	Ca	Mg	K	Na	Al	BS_e	pH
	cm	$\mu mol_c\ g^{-1}$	$\mu mol_c\ g^{-1}$	$\mu mol_c\ g^{-1}$	$\mu mol_c\ g^{-1}$	$\mu mol_c\ g^{-1}$	%	0.01 M $CaCl_2$
A	0-24	33.4	5.0	2.9	0.8	8.5	83	4.5
EA	24-34	32.5	2.1	0.4	0.6	2.7	93	4.9
2Bt	34-53	62.8	6.7	1.0	0.9	3.4	95	5.1
2EB	53-76	36.0	3.9	0.8	0.7	10.1	80	4.6
2Bt	76-93	35.5	4.1	1.0	0.7	14.3	74	4.5
3BC	93-115	14.1	2.1	0.5	0.4	10.9	61	4.3
3BC	115-150	17.0	13.1	1.1	1.0	15.2	68	4.3

Ring skov, afd. 327, Matrup distrikt

FSL forsøg:	1195
Profilbase:	15951
UTM32:	Ø 538645, N 6202108
Klassifikation:	USDA: Lamellic Hapludalf, coarse-loamy, mixed, acid, mesic WRB: Lamellic Luvisol, medium textured
Beskrevet af:	Tove Nielsen, 27. august 1998
Kote:	110 m.o.h.
Landskabstype, form:	Dødislandskab, småbakket
Træart:	Ask, plantet 1973
Udgangsmateriale:	Moræneaflejringer
Dræningsklasse:	Veldrænet
Lokalitetstype:	34

Bemærkning: Udgangsmaterialet er inhomogent. Lagdeling tyder på en sorteret aflejring. Lernedslemning kan godt have fundet sted, men det skal evt. kunne påvises som lerskin i 2 Bt. Tekstur- og humusklasser efter Den Danske Jordklassificering. Ingen O-horisont.

Beskrivelse af horisonter i jorden (inddeling 10 cm):

A	0 -	24 cm	Meget mørk grålig brun (10 YR 3/2 f) sandblandet ler, humusrig
EA	24 -	34 cm	Gullig brun (10YR 5/4 f) sandblandet ler, humusholdig
2Bt	34 -	53 cm	Mørk gullig brun (10YR 4/4 f) ler, humusfattig
2EB	53 -	76 cm	Gullig brun (10YR 5/4 f) ler, humusfattig
2Bt	76 -	93 cm	Brun (10YR 5/3 f) ler, humusfattig
3BC	93 -	115 cm	Gullig brun (10YR 5/6 f) sandblandet ler, humusfattig
3BC	115 -	150 cm	Gullig brun (10YR 5/4 f) ler, humusfattig

Stokkebjerg, afd. 193, Odsherred distrikt

FSL forsøg	1196
Profilbase:	15701
UTM32:	Ø 669380, N 6192336
Klassifikation:	USDA: Oxyaquic Hapludalf, coarse-loamy, mixed, acid, mesic WRB: Stagnic Luvisol
Beskrevet af:	Finn Vannman Jørgensen og Brian T. Vestergård, 27. april 2000
Kote:	30 m.o.h.
Landskabstype, form:	Randmorænelandskab, storbakket
Træart:	Lind, etableret 1973
Udgangsmateriale:	Moræneaflejring
Dræningsklasse:	Moderat veldrænet
Lokalitetstype:	75

Bemærkning: På skrånende terræn. Morænen er kalkholdig fra dybden 215 cm.

Beskrivelse af horisonter i jorden (inddeling 20 cm):

Oi	-5 - 0 cm
A1	0 - 2 cm
A2	2 - 15 cm
AE	15 - 34 cm
E	34 - 77 cm
2Btg	77 - 140 cm

Oi. Litterlag

A1. Meget mørk brun (10 YR 2/2 f) lerblandet sand; meget humusrig, 10-20% sten af blandet form, størrelse og type; struktur (f), let smuldrende konsistens; få fine porer; meget hyppige af rødder af alle størrelser med tilfældig fordeling; horisontgrænse abrupt og bølget

A2. Mørk gulligbrun (10YR 3/6 f) lerblandet sand; humusrig; 10-20% sten; angulær struktur (f); let smuldrende konsistens; få fine porer; meget hyppige rødder af alle størrelser med tilfældig fordeling; horisontgrænse klar og bølget

AE. Mørk gullig brun (10 YR 4/6 f) lerblandet sand; humusholdig; 10-20% sten af blandet form størrelse og type; angulær struktur (f); smuldrende konsistens; en del medium porer; hyppige rødder af alle størrelser med tilfældig fordeling; horisontgrænse gradvis og bølget

E. Lys oliven brun (2.5Y 5/4 f) lerblandet sand; humusfattig; 10-20% brogede store diffuse jernudfældningspletter; 10-20% sten af blandet form størrelse og tilstand; mellemstore hårde (tjek) afrundede noduler (Fe-oxider/hydroxider); angulær struktur (f); let smuldrende konsistens; en del medium porer; nogle rødder af alle størrelser med tilfældig fordeling; horisontgrænse gradvis og irregulær

2Btg. Gullig brun (10 YR 5/4 f) ler; humusfattig; 0-10% grålige slirer på brun bund; lodret stribede store pletter med klar grænse; 10-20% sten af blandet form, størrelse og tilstand; angulær struktur (f); smuldrende konsistens; mange porer af varierende størrelse; nogle rødder af alle størrelser med tilfældig fordeling.

Stokkebjerg, afd. 193, Odsherred distrikt

Hori-zon	Depth cm	BD $g\ cm^{-3}$	clay %	silt %	fine sand %	coar. sand %	C $mg\ g^{-1}$	N $mg\ g^{-1}$	P $mg\ kg^{-1}$
Oi	-5-0						396.9	17.2	
A1	0-2	0.29	8	12	57	23	63.1	4.4	72
A2	2-15	1.27	9	15	51	25	24.5	1.8	57
AE	15-34	1.40	8	11	47	34	5.8	0.5	119
E	34-77	1.61	7	10	58	25	1.3	0.1	189
2Btg	77-140	1.84	15	11	37	36	1.0	0.1	257

Hori-zon	Depth cm	Ca $\mu mol_c\ g^{-1}$	Mg $\mu mol_c\ g^{-1}$	K $\mu mol_c\ g^{-1}$	Na $\mu mol_c\ g^{-1}$	Al $\mu mol_c\ g^{-1}$	BS_e %	pH 0.01 M $CaCl_2$
Oi								n.a.
A1	0-2	25.6	8.3	4.3	3.0	n.a.	-	3.5
A2	2-15	5.3	1.9	1.0	1.3	n.a.	-	3.6
AE	15-34	1.7	0.7	0.4	0.8	n.a.	-	4.0
E	34-77	3.3	2.3	0.3	1.1	n.a.	-	4.2
2Btg	77-140	24.1	22.3	1.4	3.1	n.a.	-	4.3

Data printed with permission from Vesterdal and Vanman-Jørgensen, Danish Forest and Landscape Research Institute.

Viemose skov, afd. 27, Petersgård distrikt

Hori-zon	Depth cm	BD $g\ cm^{-3}$	clay %	silt %	fine sand %	coar. sand %	C $mg\ g^{-1}$	N $mg\ g^{-1}$	P $mg\ kg^{-1}$
A	0-11	1.10	11	22	43	24	23.3	1.9	21
E	11-43	1.60	18	20	40	22	4.9	0.5	15
Bt(g)1	43-70	1.63	24	20	36	20	2.7	0.3	30
Bt(g)2	70-101	1.71	25	20	38	17	2.0	0.3	108
BCk(g)	101-130	n.a..	22	23	36	19	-	0.2	342
Ck(g)	130-140	n.a..	21	23	38	17	-	0.1	294

Hori-zon	Depth cm	Ca $\mu mol_c\ g^{-1}$	Mg $\mu mol_c\ g^{-1}$	K $\mu mol_c\ g^{-1}$	Na $\mu mol_c\ g^{-1}$	Al $\mu mol_c\ g^{-1}$	BS_e %	pH 0.01 M $CaCl_2$
A	0-11	11.3	4.1	1.3	0.3	29.7	37	3.8
E	11-43	9.6	3.4	0.8	0.4	41.4	26	3.8
Bt(g)1	43-70	37.1	17.8	1.5	1.0	23.4	71	4.1
Bt(g)2	70-101	53.8	16.2	1.6	1.4	6.3	92	4.6
BCk(g)	101-130	-*	5.8	1.3	1.4	0.0	-	7.5
Ck(g)	130-140	-*	4.1	1.2	1.3	0.0	-	7.7

*8.1% $CaCO_3$ i BCk(g), 20.2% $CaCO_3$ i Ck(g)

Viemose skov, afd. 27, Petersgård distrikt

FSL forsøg:	1197
Profilbase:	16031
UTM32:	Ø 701879, N 6101489
Klassifikation:	USDA: Typic Hapludalf, fine-loamy, mixed, acid, mesic WRB: Luvisol, medium textured
Beskrevet af:	Ingeborg Callesen og Tove Nielsen, 29. august 1998
Kote:	12 m.o.h.
Landskabstype og form:	Dødislandskab, svagt kuperet
Træart:	Ask, plantet 1973
Udgangsmateriale:	Moræneaflejringer
Dræningsklasse:	Veldrænet
Lokalitetstype:	35

Beskrivelse af horisonter i jorden (inddeling 10 cm):

A	0 - 11 cm
E	11 - 43 cm
Bt(g)1	43 - 70 cm
Bt(g)2	70 - 101 cm
BCk(g)	101 - 130 cm
Ck(g)	130 - 140 cm

A. Meget mørk grålig brun (10YR 3/2 f) sandblandet ler; humusrig; krummestruktur; meget hyppige tilfældigt forekommende rødder af forskellige størrelser; horisontgrænse klar og jævn

E. Brun (10YR 5/3 f) ler; humusfattig; medium granulær og subangulær struktur med henholdsvis svag og stærk stabilitet; løs konsistens; 0-10% afrundede forvitrede sten af forskellige størrelser; spredte tynde humusbelægninger i porer og kanaler nogle tilfældigt forekommende rødder af forskellige størrelser; horisontgrænse klar og jævn

Bt(g)1. Mørkebrun (10YR 4/3 f) ler; humusfattig; grov subangulær struktur med medium til stærk stabilitet; let smuldrende konsistens; 0-10% afrundede forvitrede sten af forskellige størrelser; små bløde irregulære jern og mangankonkretioner fra dybden 48 cm; meget få tilfældigt forekommende rødder af forskellige størrelser; regnormeaktivitet; horisontgrænse gradvis og jævn

Bt(g)2. Mørkebrun (10YR 4/3 f) svær ler; humusfattig; grov subangulær struktur med medium til stærk stabilitet; smuldrende konsistens; enkelte kalknoduler; 0-10% afrundede uforvitrede sten; små bløde irregulære jern- og mangankonkretioner (flere end i Bt(g)1); spredte tynde lerskin; meget få tilfældigt forekommende rødder af forskellige størrelser; regnorme; horisontgrænse diffus og jævn

BCk(g). Gullig brun (10YR 5/4 f) ler; humusfattig; grove stabile subangulære blokke; små bløde jern- og mangankonkretioner; kalknoduler og spredt i matrix

Ck(g). Bleg brun (10YR 6/3 f) ler; humusfattig; grov subangulær struktur; kalkholdig, både som noduler og i matrix; små bløde jern- og mangankonkretioner; meget få tilfældigt forekommende rødder af forskellige størrelser

Tågerød skov, afd. 167 Vallø Stifts distrikt

FSL forsøg:	1198
Profilbase:	15341
UTM33:	Ø 314097, N 6145755
Klassifikation:	USDA: Oxyaquic Hapludalf, coarse-loamy, mixed, nonacid, mesic WRB: Stagnic Luvisol, medium textured
Beskrevet af:	Ingeborg Callesen, 19. oktober 2000
Kote:	50 m.o.h.
Landskabstype og form:	Dødislandskab, meget svagt kuperet, fladt
Træart:	Bøg, plantet 1973
Udgangsmateriale:	Moræneaflejringer
Dræningsklasse:	Moderat veldrænet
Lokalitetstype:	75

Beskrivelse af horisonter i jorden (inddeling 10 cm):

Oi	-1	-	0	cm
A	0	-	12	cm
A/E	12	-	36	cm
Bt(g)1	36	-	68	cm
Bt(g)2	68	-	110	cm
C(g)1	110	-	120	cm
C(g)2	180	-	190	cm

Oi. Løs bøgelitter, kviste og knopskæl, horisontgrænse abrupt og jævn

A. Meget mørk gråbrun (10 YR 3/2 f) lerholdigt siltet sand; humusrig; løs konsistens (f); hyppige rødder af alle størrelser med tilfældig fordeling; mange anemonerødder; horisontgrænse gradvis og bølget

A/E. Lys gullig brun (2.5Y 6/4 f) og mørk gråbrun (10YR 4/2 f) leret siltet sand; humusholdig; våde afblegede farver; krummestruktur (f); løs konsistens; hyppige rødder af alle størrelser med tilfældig fordeling; horisontgrænse gradvis og jævn

Bt(g)1. Brun (10YR 5/3 f) ler; humusholdig; 20-30% kraftigt brune pletter (7.5 YR 5/6 f); grålige slirer; små irregulære afrundede Fe- og Mn-oxider/hydroxider; subangulær struktur; fine ustabile aggregater; løs konsistens (f); meget få fine og mellemgrove rødder med tilfældig fordeling; mange rådne sten af krystallinsk oprindelse; horisontgrænse diffus og jævn

Bt(g)2. Gullig brun (10 YR 5/4 f) ler; humusfattig; mørke gullig brun (10YR 4/4 f) og lyse gullig brune (2.5Y 6/3 f) brogede store redoxpletter; 0-10% mellemstore irregulære sten; medium store moderat stabile angulære blokke (f); løs konsistens; spredte tynde humusbelægninger og clayskins i porer, kanaler og på aggregatoverflader, meget få fine og mellemgrove rødder med tilfældig fordeling; horisontgrænse klar og jævn

C(g)1. Gullig brun (10 YR 5/4 f) ler; humusfattig; gullig brune (10 YR 5/4 f) pletter på grålig eller blålig bund; 0-10% mellemstore irregulære sten; angulær struktur; medium store moderat stabile aggregater; løs konsistens (f); meget få fine og mellemgrove rødder; tilfældig fordeling

C(g)2. Gullig brun (10 YR 5/4 f) ler; humusfattig; redoxpletter på grålig eller blålig bund; indeholder ikke kalk; angulær struktur; medium moderat stabile aggregater; løs konsistens (f)

Tågerød skov, afd. 167 Vallø Stifts distrikt

Horizon	Depth cm	BD g cm^{-3}	clay %	silt %	fine sand %	coar. sand %	C mg g^{-1}	N mg g^{-1}	P mg kg^{-1}
Oi	-1-0						380.8	16.4	
A	0-12	1.02	10	19	41	31	23.1	1.7	21
A/E	12-36	1.42	11	17	39	33	8.3	0.6	13
Bt(g)1	36-68	1.67	20	17	41	23	1.5	0.2	144
Bt(g)2	68-110	1.58	15	11	41	32	1.2	0.2	211
C(g)1	110-120	1.65	15	10	41	34	1.2	0.2	218
C(g)2	180-190		19	20	39	21	1.2	0.2	232

Horizon	Depth cm	Ca µmol$_c$ g^{-1}	Mg µmol$_c$ g^{-1}	K µmol$_c$ g^{-1}	Na µmol$_c$ g^{-1}	Al µmol$_c$ g^{-1}	BS$_e$ %	pH 0.01 M $CaCl_2$
Oi	-1-0							4.8
A	0-12	24.4	4.3	2.1	0.5	0.0	-	4.0
A/E	12-36	21.4	2.7	0.4	0.4	14.0	64	4.3
Bt(g)1	36-68	63.0	10.0	3.0	1.2	2.5	97	5.1
Bt(g)2	68-110	63.0	5.8	1.4	0.8	0.6	99	5.5
C(g)1	110-120	77.1	3.6	1.3	0.8	0.0	100	6.1
C(g)2	180-190	101.0	3.2	2.4	1.1	0.0	100	6.7

Grevindeskoven, afd. 69-70, Wedellsborg

Horizon	Depth cm	BD $g\ cm^{-3}$	clay %	silt %	fine sand %	coar. sand %	C $mg\ g^{-1}$	N $mg\ g^{-1}$	P $mg\ kg^{-1}$
A	0-35	1.04	22	31	31	16	26.7	2.6	39
AE	35-56	1.34	23	26	34	17	14.7	1.4	42
Bt(g)1	56-65	1.40	29	24	32	16	7.3	0.8	105
Bt(g)2	65-93	1.57	31	33	26	9	3.5	0.4	285

Horizon	Depth cm	Ca $\mu mol_c\ g^{-1}$	Mg $\mu mol_c\ g^{-1}$	K $\mu mol_c\ g^{-1}$	Na $\mu mol_c\ g^{-1}$	Al $\mu mol_c\ g^{-1}$	BS_e %	pH 0.01 M $CaCl_2$
A	0-35	129.0	19.8	1.9	2.5	1.0	99	5.0
AE	35-56	165.9	12.6	1.3	2.7	0.0	100	6.4
Bt(g)1	56-65	189.2	14.6	2.0	3.6	0.0	100	6.7
Bt(g)2	65-93	191.6	15.4	2.6	4.2	0.0	100	6.9

Grevindeskoven, afd. 69-70, Wedellsborg

FSL forsøg	1199
Profilbase:	16041
UTM32:	Ø 553514, N 6140297
Klassifikation:	USDA: Oxyaquic Argiudoll, fine-loamy, mixed, nonacid, mesic WRB: Luvic Phaeozem, medium textured
Beskrevet af:	Tove Nielsen, 15. januar 1999
Kote:	5 m.o.h.
Landskabstype, form:	Moræneflade
Træart:	Ask, plantet 1973
Udgangsmateriale:	Moræneaflejringer
Dræningsklasse:	Ufuldstændigt drænet
Lokalitetstype:	86

Beskrivelse af horisonter i jorden:

A	0 -	35 cm
AE	35 -	56 cm
Bt(g)1	56 -	65 cm
Bt(g)2	65 -	93 cm

A. Meget mørk gråbrun (10YR 3/2 f) siltet ler; humusrig; ikke klæbende konsistens; 0-10% sten afrundede sten af forskellige størrelser og typer; meget hyppige tilfældigt forekommende rødder af forskellige størrelser; horisontgrænse gradvis og jævn

AE. Mørkebrun (10YR 3/3 f) siltet ler; humusholdig; ikke klæbende konsistens; 0-10% sten afrundede sten af forskellige størrelser og typer; hyppige tilfældigt forekommende rødder af forskellige størrelser; horisontgrænse gradvis og jævn

Bt(g)1. Meget mørk gråbrun (2.5Y 3/2 f) siltet ler; humusholdig; moderat stærke subangulære blokke af forskellig størrelse; svagt klæbende konsistens; 0-10% afrundede sten af forskellige størrelser og typer; hyppige tilfældigt forekommende rødder; horisontgrænse diffus og bølget

Bt(g)2. Grålig brun (2.5Y 5/2 f) siltet svær ler; humusfattig; kraftigt brune redoxpletter; moderat stærke subangulære blokke af forskellig størrelse; kompakt; svagt klæbende konsistens; 0-10% afrundede sten af forskellige størrelser og typer

Kragelund, Silkeborg plantningsforening

Profilbase:	15351
UTM32:	Ø 526679, N 6225937
Klassifikation:	USDA: Arenic Hapludult, coarse-loamy, acid WRB: Arenic Alisol, coarse textured
Beskrevet af:	Ingeborg Callesen. 20. september 2000
Kote:	88 m.o.h.
Landskabstype, form:	Moræneflade, svagt bølget topografi
Træart:	Bøg, plantet 1961
Udgangsmateriale:	Flyvesand over moræneaflejringer
Dræningsklasse:	Veldrænet
Lokalitetstype:	33

Beskrivelse af horisonter i jorden (10 cm inddeling):

Oi	-1 -	0 cm
Ap	0 -	27 cm
A	27 -	40 cm
Bs1	40 -	60 cm
Bs2	60 -	89 cm
Bt(g)	89 -	120 cm
C	120 -	160 cm

Oi. Hyppige fine rødder med tilfældig fordeling; horisontgrænse abrupt og jævn

Ap. Meget mørk gråbrun (10 YR 3/2 f) svagt lerholdigt siltet sand; humusholdig; krummestruktur; fine ustabile aggregater (t); ikke hyppige rødder af alle størrelser med tilfældig fordeling ;pløjet; horisontgrænse klar og jævn

A. Mørk gullig brun (10YR 3/4 f) lerholdigt siltet sand; humusholdig; 0-10% mellemstore sten; krummestruktur; fine ustabile aggregater (f); hyppige rødder af alle størrelser med tilfældig fordeling; horisontgrænse gradvis og jævn

Bs1. Mørk gullig brun (10 YR 4/6 f) lerholdigt siltet sand; humusfattig; 0-10% sten; strukturløs; svagt klæbende (f); hyppige rødder af alle størrelser med tilfældig fordeling; horisontgrænse gradvis og jævn

Bs2. Brungul (10 YR 6/6 f) lerholdigt siltet sand; humusfattig; 0-10% mellemstore sten; subangulær struktur; medium store ustabile aggregater; meget klæbende (f); nogle fine rødder; horisontgrænse klar og jævn

Bt(g). Gullig brun (10YR 5/6 f) leret siltet sand og finsand; humusfattig; bleg gule (2.5Y 7/3 f) diffuse jernudfældningspletter med kraftigt brun (7.5YR 5/8 f) kant; lerudfældninger i horisontale bånd; 0-10% mellemstore sten; subangulær struktur; medium store moderat stabile aggregater; meget klæbende; nogle fine rødder; horisontgrænse gradvis og jævn

C. Gullig brun (10YR 5/6 f); leret siltet sand; moræneaflejringer; humusfattig; 0-10% sten

Kragelund, Silkeborg plantningsforening

Hori-zon	Depth	BD	clay	silt	fine sand	coar. sand	C	N	P
	cm	g cm^{-3}	%	%	%	%	mg g^{-1}	mg g^{-1}	mg kg^{-1}
Oi	-1-0						358.0	13.8	
Ap	0-27	1.14	5	4	30	61	9.1	0.5	18
A	27-40	1.25	6	5	28	60	8.6	0.5	14
Bs1	40-60	1.24	7	7	38	48	6.7	0.4	37
Bs2	60-89	1.69	8	7	43	42	1.6	0.1	33
Bt(g)	89-120	1.65	11	8	41	40	1.0	0.1	17
C	120-160		10	6	41	43	0.8	0.1	50

Hori-zon	Depth	Ca	Mg	K	Na	Al	BS_e	pH
	cm	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	µmol_c g^{-1}	%	0.01 M $CaCl_2$
Oi	-1-0							4.6
Ap	0-27	1.4	0.4	0.2	0.2	10.3	18	3.9
A	27-40	1.1	0.3	0.0	0.1	11.2	11	4.4
Bs1	40-60	0.7	0.2	0.0	0.1	10.3	9	4.5
Bs2	60-89	1.6	0.6	0.1	0.1	10.9	18	4.5
Bt(g)	89-120	6.0	1.5	0.4	0.5	25.6	25	4.2
C	120-160	4.3	1.8	0.3	0.6	23.7	23	4.1

II. Klima (in Danish)

Klimadata er brugt i paper I og i forbindelse med klassifikation (App. I).

Tabel II.a Årlig nedbør (P), potentiel fordampning (Ep), globalstråling (GR), temperatur (T) og nedbørsoverskud (P-Ep). Normalværdierne er interpoleret fra nærmestliggende klimastationer i en radius på indtil 10 km. *Kilde: Danmarks Jordbrugsforskning og Danmarks Meteorologiske Institut.*

ID	Distrikt	P	Ep	GR	T	P-Ep
				årsnormal 1964-1998		
		mm	mm	MJ m^{-2}	°C	mm
1003	Bregentved	637	574	3540	7.8	63
1004	Christianssæde	600	584	3574	8.1	17
1005	Frijsenborg	683	556	3467	7.5	127
1006	Holsteinborg	583	577	3570	7.9	5
1007	Lindet	848	553	3436	7.7	295
1008	Løvenholm	613	562	3503	7.4	51
1009	Palsgård	838	550	3399	7.3	288
1010	Skjoldenæsholm	640	574	3546	7.7	66
1011	Frederiksborg	668	565	3488	7.8	103
1012	Gråsten	738	556	3445	8.0	182
1013	Hanherred	713	553	3482	7.3	160
1014	Ulborg	881	550	3414	7.5	331
1015	Nørlund	701	553	3463	7.3	148
1195	Matrup	783	553	3457	7.5	230
1196	Odsherred	579	574	3552	8.0	5
1197	Petersgård	603	577	3546	8.1	26
1198	Vallø Stifts	625	568	3522	7.7	57
1199	Wedellsborg	658	568	3484	7.8	90
2000	Silkeborg Pl.f.	703			7.5	

Tabel II.b Normalværdier for nedbør (P), potentiel fordampning (Ep), globalstråling (GR) og nedbørsoverskud (P-Ep) i vækstsæsonen fra 1. maj - 1. november. Normal 1964-1998. Interpolation fra omkringliggende klimastationer i en radius på indtil 10 km. *Kilde: Danmarks Jordbrugsforskning og Danmarks Meteorologiske Institut.*

ID	Distrikt	P	Ep	GR	P-Ep[a]
		1. maj - 1. november, 1964-1998			
		mm	mm	MJ m^{-2}	mm
1003	Bregentved	347	460	2658	-125
1004	Christianssæde	322	469	2680	-155
1005	Frijsenborg	368	445	2603	-94
1006	Holsteinborg	325	463	2677	-152
1007	Lindet	466	438	2560	5
1008	Løvenholm	334	451	2633	-129
1009	Palsgård	435	438	2542	-15
1010	Skjoldenæsholm	350	460	2661	-118
1011	Frederiksborg	371	454	2621	-87
1012	Gråsten	396	441	2578	-53
1013	Hanherred	396	445	2627	-76
1014	Ulborg	475	438	2541	16
1015	Nørlund	380	441	2609	-77
1195	Matrup	411	441	2591	-48
1196	Odsherred	322	460	2661	-142
1197	Petersgård	322	463	2670	-149
1198	Vallø Stifts	337	457	2643	-126
1199	Wedellsborg	359	454	2606	-103
2000	Silkeborg Pl.f.	373			

[a]Gennemsnit for 1964-1998, og derfor ikke differencen mellem P og Ep kolonnerne, som er normaler for perioden.